EFFECT UPON ENVIRONMENT OF BRINE CAVITY SUBSIDENCE AT GROSSE ILE, MICHIGAN — 1971

By: Kenneth K. Landes, Thomas B. Piper

April 1972

Cover: View of Point Hennepin brine field, Grosse Ile, and downriver section of Detroit River, Detroit, Michigan looking north. Well sites are visible in foreground. Central gallery sinkhole, about three-quarters developed, is the water-filled crater at center. The north gallery sinkhole is partially visible toward upper end of the island. This photo was selected to establish the concept to be developed in the report that while real, the sinkholes represent relatively minor disturbances to the brine field and imperceptible damage to the surrounding community.

EFFECT UPON ENVIRONMENT OF BRINE CAVITY SUBSIDENCE

AT GROSSE ILE, MICHIGAN, 1971

by

Kenneth K. Landes, Consulting Geologist (1)

Thomas B. Piper, Manager of Wells,
BASF Wyandotte Corp. (2)

April, 1972

(1) 1005 Berkshire Rd., Ann Arbor, MI 48104
(2) Wyandotte, MI 48192
(3) 2635 Flossmoor Road, Flossmor, IL 60422

CONTENTS

ILLUSTRATIONS

Cover: Air View, Hennepin Point

Photos, figures 9, 10, 14 courtesy of Detroit Edison Company

SUMMARY

Artificial brine production began in the Detroit area in 1895. Out of many subsequent operations in Michigan and neighborning Ontario, from which many millions of tons of salt were produced, there have been only two localities where collapse of the cavern roofs has penetrated to the surface. These were at Windsor, Ontario, in 1954 and on Grosse Ile in the Detroit River below Detroit in 1971.

This report is primarily concerned with an investigation into the effect of the Grosse Ile occurrence upon the environment; both surface and subsurface values will be considered. By virtue of its similarity in geologic setting and impact, the Windsor occurrence, now 20 years into history, is available for examination and offers support to the authors' conclusion that the environmental impact of a salt well sinkhole is nominal and that the activity is limited to the immediate area around the wells, and is arrested upon terminat on of operation of the well gallery involved.

The mechanics of sinkhole formation is not treated in this report. It is currently the subject of a separate Solution Mining Research Institute-sponsored investigation and will be covered in a separate report.

The northern end of Grosse Ile, Point Hennepin, is owned by Wyandotte Chemicals Company, now BASF Wyandotte Corporation, and was originally purchased as a place to pond wastes from the chemical plants on the mainland to the west. The fine-grained light-colored tailings were delivered in slurry form by pipeline to the island where they were ponded and drained. The maximum thickness is 30 feet; beneath is a few feet of organic soil at and below river level. Most of Grosse Ile is a glacial moraine consisting of about 60 feet of clay with scattered boulders. Between the top of the bedrock and the top of the salt measures is 500 feet of nearly flat stratified rock consisting in descending order of impure dolomite, sandstone, and more impure dolomite. The rock section that contains the salt is about 730 feet in thickness; the more massive salt beds brined are toward the base, at depths between 1100 and 1300 feet.

Salt production by the brining method (solution mining) involves pumping fresh water into the salt beds through imout wells and removing the brine through production wells. This operation results in cavities, referred to as "galleries," in the salt formation. Solution mining had been in operation on Point Hennepin for nearly 20 years when, in November 1969, cracks first were observed at the surface above the North Gallery. One year later settling became noticeable, resulting in pipeline breaks. On 9 January 1971 cratering started, and several months later the sinkhole reached its present configuration. On 28 April, 1971, collapsing started above the Central Gallery about one-half mile away,

without prior surface cracking or pipeline failures. The result was a second separate sinkhole, this one with a satellite. The Central Gallery cratering also took several months to reach its present size and shape.

A "line of zero cracks" was drawn around each sinkhole, enclosing the area of surface activity. Each lies within the underlying gallery boundaries, and had not changed appreciably at the time this was written, approximately a year later.

Other areas of the brine field are not involved in the activity and operations continue undisturbed. Observations of precise level elevation monuments indicate stability has been restored to the disturbed area; duplicating that achieved at Windsor subsequent to 1954.

Although salt sinkholes are scarce in the Michigan-Ontario district, solution mining of salt has resulted in sinkhole formation in many other parts of the world including New York State, the Gulf Coast, Kansas, Saskatchewan, Virginia, and notably in England, where an entire district is involved. Subsidence of the earth's surface has also resulted from excessive pumping of fluids (water, oil) from Texas, California, and South Africa. The removal of coal and ore in underground mines has brought about surface collapse in many areas of Michigan and elsewhere.

However, these man-made depressions on the surface are insignificant compared with those produced by nature. Sinkholes are abundant the world over, wherever there are soluble rocks (limestone, salt, gypsum) near the surface where percolating waters can dissolve out great caverns. Both the caves and the sink pitted ("Karst") surfaces are popular scenic features.

Michigan law prohibits well drilling and operation that results in either underground or surface waste. "Waste" is defined as "damage or injury" to "potable water, mineralized water, or other subsurface resources" or to "destruction of surface waters, soils, animal, fish and aquatic life or surface property;" by these criteria, there has been little waste.

This investigation yielded no evidence of damage or injury to any animal or plant, soil or mineral resource, or underground or surface water resource. The only effect has been to the topographic surface; this is limited to two partially water-filled steepwalled craters, one single and one double, which interrupt the flat surface of the waste pile. Immediately after collapse, the craters were features of considerable local interest, and guards were employed as a safety precaution. Eventually these sinkholes could become a scenic or recreational feature, as are many abandoned quarries, or used for storage of material to be reclaimed later, or for waste disposal.

It is our opinion that sinkholes do not extend beyond the area of the underlying gallery, and those on Point Hennepin have had no harmful effect on the environment. Both sinkholes and non-collapsed galleries can be of service to the community.

INTRODUCTION

Explanation. This report was motivated by the sudden development of two sinkholes, due to the collapse of brine cavern roofs, on northern Grosse Ile in the Detroit River in early 1971. Because of their proximity to urban residential and industrial areas, this occurrence resulted in considerable attention both in the neighborhood and in the press. Fears of possible involvement of adjacent property and environmental damage brought about state-wide concern. This study is an appraisal of the actual effects the sinkholes have had on the environment, based upon studies of both man-made and natural sinkholes elsewhere as well as on the Grosse Ile sinkholes in particular. The year that has elapsed since stability resumed on Grosse Ile has brought about an almost complete dimunution of apprehension.

The preparation of this report has been sponsored jointly by the Solution Mining Research Institure (SMRI), a technical association of companies engaged in salt production by solution mining, and the BASF Wyandotte Corporation (formerly Wyandotte Chemicals Corporation, and prior to that, Michigan Alkali Company).
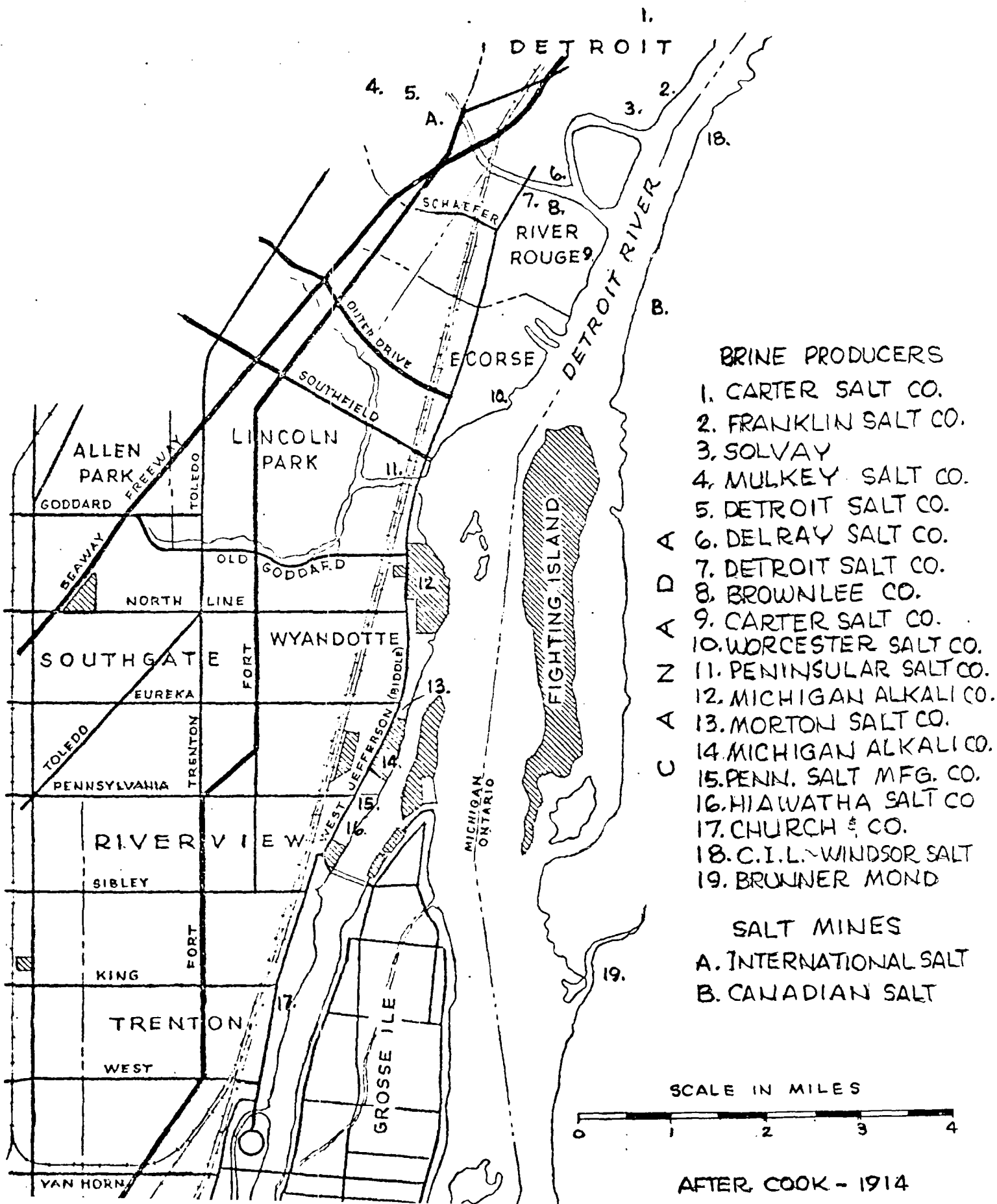
History. Salt was produced in Michigan by evaporating natural brines obtained from springs by both Indians and early settlers. Attempts at well drilling in the vicinity of the salt springs to increase brine production began in 1838, but were unsuccessful. The first commercial development was at Saginaw in 1859 when a salt manufacturing company was organized, pumping natural brine from a sandstone that varies in depth in this area from 650 to 800 feet (Cook, 1911, p. 316-319). From Saginaw the production of salt from natural sandstone brines spread up the Saginaw Valley, around the shores of Saginaw Bay, and along the Lake Huron coast as far north as Oscoda. Salt-making was a handmaiden of the lumbering industry. The fuel used to evaporate the brine was sawmill waste; when lumbering ceased in the area underlain by the brine-yielding sandstone, the sawmills and sooner or later most of the brine plants closed for good.

Salt production from artificial brines obtained by pumping fresh water through drilled wells into a rock salt formation began in the Detroit area in 1895, and in 1906 a shaft was sunk to mine the salt. Although since 1895 a total of about 20 brine plants have been operated in the Detroit area (Figure 1) for the purpose of producing evaporated salt for table and agricultural use, only one remains in this business today. Instead, the artificial brine obtained here is used in the manufacture of chemicals based upon the sodium or the chlorine in the salt. This phase of the salt-brine industry began in the preceeding century; today it ranks far above table and agricultural uses in annual tonnage mined by solution of rock salt.

The large volumes of salt dissolved from beneath the surface to satisfy the chemical market has resulted in cavities in the bedrock salt deposits. In some places the cavity roofs have failed, producing surface effects that range from gentle, almost imperceptible subsidence over large areas, to localized surface craters known as sinkholes. In all cases these effects have been confined to the area of the wells. Similar depressions result from the natural dissolving of near-surface soluble rocks by percolating waters, producing first a cavern and sometimes a sinkhole. Limestone is the most widespread soluble rock, and many limestone areas are pockmarked by such sinks. The roofs of underground openings produced by mining may also collapse, resulting in similar craters at the surface.

EARLY SALT OPERATIONS IN THE DETROIT AREA

FIG. 1

BRINE PRODUCERS
1. CARTER SALT CO.
2. FRANKLIN SALT CO.
3. SOLVAY
4. MULKEY SALT CO.
5. DETROIT SALT CO.
6. DELRAY SALT CO.
7. DETROIT SALT CO.
8. BROWNLEE CO.
9. CARTER SALT CO.
10. WORCESTER SALT CO.
11. PENINSULAR SALT CO.
12. MICHIGAN ALKALI CO.
13. MORTON SALT CO.
14. MICHIGAN ALKALI CO.
15. PENN. SALT MFG. CO.
16. HIAWATHA SALT CO
17. CHURCH & CO.
18. C.I.L.—WINDSOR SALT
19. BRUNNER MOND

SALT MINES
A. INTERNATIONAL SALT
B. CANADIAN SALT

SCALE IN MILES
0 1 2 3 4

AFTER COOK – 1914

Salt brining has been responsible for sinkholes in many parts of the world. The Cheshire area of northwest England is a classic example, which dates back to Roman times. Numerous other examples of sinkholes are to be found in the United States as at Syracuse, New York, due to brining of bedded salt, and near Baton Rouge, Louisiana, where the operations are in a salt dome type deposit. A sinkhole resulting from production of brine for chemical manufacture occurred in the Detroit area in 1954 at the plant of Canadian Industries, Ltd. at Windsor, Ontario. In this case the crater was back filled, stability was restored, and the area has resumed its original function.

The sinkholes which formed on the Grosse Ile brine field of BASF Wyandotte Corporation in the first 4 months of 1971 are the result of salt production by the solution mining method covering a period of almost thirty years. For the first time, complete brine well records including water input and dissolved salt production data, plus precise surface elevations, are available for investigation into, and analysis of, the mechanism of surface subsidence and sinkhole formation. The rapid and dramatic craterings of the surface on northern Grosse Ile on 9 January and 29 April, 1971, aroused both public interest and trepidation. This led to the decision to investigate not only the mechanics of the collapsing, but also its impact on the environment, including both surface and subsurface waters and mineral resources. This report considers the latter matters. The actual mechanics of sinkhole formation falls in the scope of engineering known as rock mechanics. The Solution Mining Research Institute and BASF Wyandotte Corporation are sponsoring investigations into the sinkhole mechanism, although present indications are that modern well-operation techniques will preclude their formation.

Location. Grosse Ile is in the Detroit River (Figure 2) adjacent to the city of Wyandotte, a suburb of Detroit. The Grosse Ile brine field occupies Point Hennepin, at the north tip of Grosse Ile and separated from the rest of Grosse Ile by a lagoon. Point Hennepin is 1-1/4 miles long and 1/4 mile wide, and covers approximately 200 acres.

The brine field serves the chlorine and soda ash manufacturing facilities of BASF Wyandotte Corporation on the mainland; brine is delivered by pipeline under the Trenton Channel of the Detroit River which is approximately 1,000 feet wide at this point.
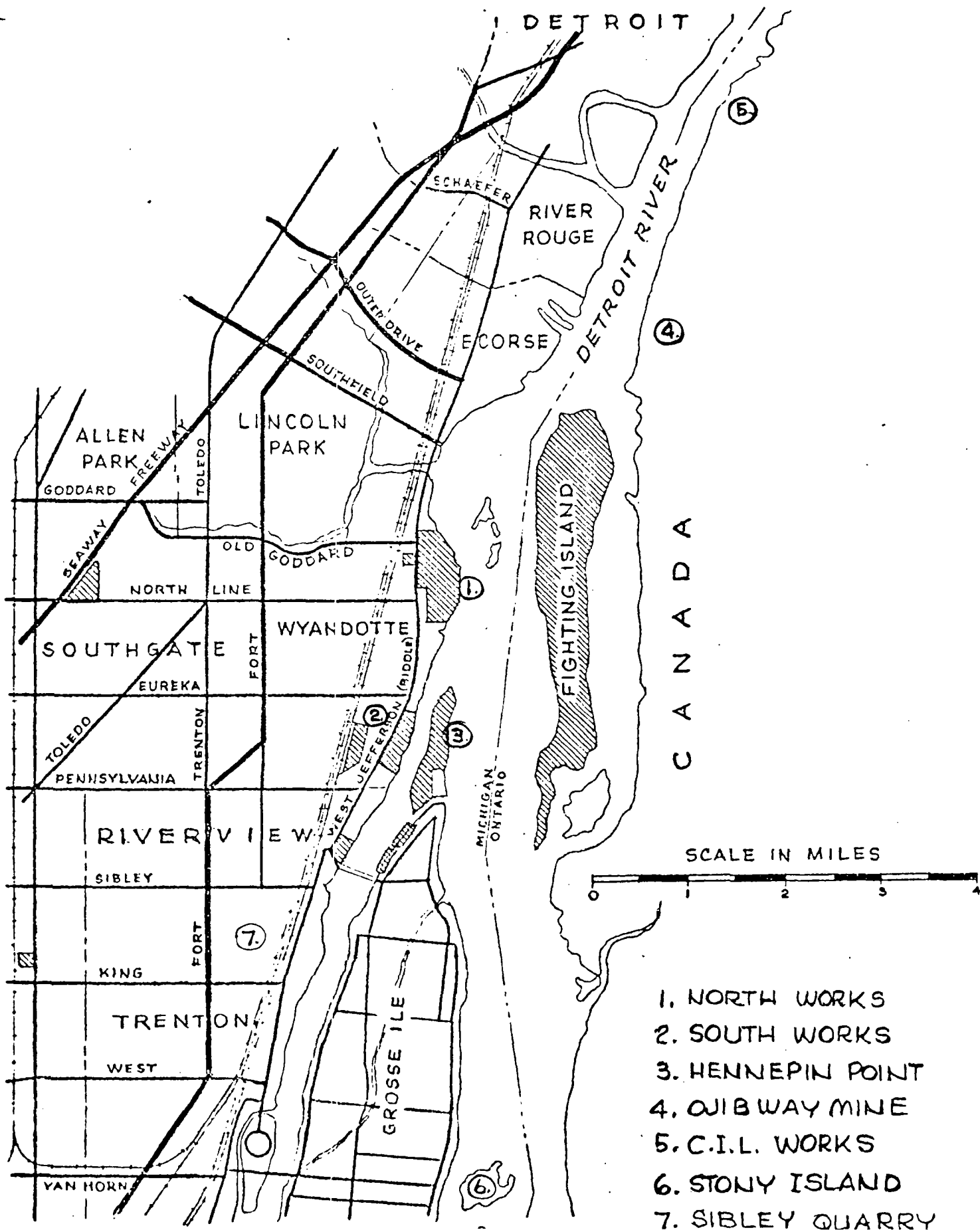
Topography. Prior to the development of salt wells, the Point Hennepin area of Grosse Ile was used for the disposal of tailings resulting from the manufacture of soda ash at the BASF Wyandotte plants in Wyandotte. The tailings were transported to the island by pipeline, ponded, and allowed to settle. The material accumulated to a height of approximately 30 feet above river level before the disposal was terminated in 1948-50. Brine production started to a limited extent in 1941 on Point Hennepin around the perimeter of the island concurrent with the ponding operation. Prior to this time brine was produced from wells located within the plants themselves on the mainland. Upon termination of tailings disposal and the adequate drying and solidification of waste material, access roads were built and wells were drilled over the rest of Point Hennepin.

The material has since become sparsely covered by volunteer vegetation. Most of the well operations were on the top of this 30 foot high tailing plateau.

The geographic framework for the brine field can be seen on the U.S. Geological Survey 7-1/2 minute Wyandotte Quadrangle topographic map and on the Detroit South Half sheet which is also on a scale of 1:24,000. Channels, water depths, and shore lines are shown on U.S. Lake Survey Chart 41 (1969).

INDEX MAP - DETROIT · GROSSE ILE AREA

FIG. 2

DETROIT

RIVER ROUGE

SCHAEFER

OUTER DRIVE

ECORSE

DETROIT RIVER

SOUTHFIELD

ALLEN PARK

LINCOLN PARK

GODDARD

SEAWAY

FREEWAY

TOLEDO

OLD GODDARD

NORTH LINE

FIGHTING ISLAND

①

WYANDOTTE

SOUTHGATE

FORT

EUREKA

TOLEDO

TRENTON

PENNSYLVANIA

WEST JEFFERSON (BIDDLE)

②

③

MICHIGAN ONTARIO

CANADA

RIVERVIEW

SIBLEY

FORT

⑦

KING

GROSSE ILE

TRENTON

WEST

VAN HORN

⑥

SCALE IN MILES

0   1   2   3   4

1. NORTH WORKS
2. SOUTH WORKS
3. HENNEPIN POINT
4. OJIBWAY MINE
5. C.I.L. WORKS
6. STONY ISLAND
7. SIBLEY QUARRY

GEOLOGY

Stratigraphy (Figure 3). Except for the perimeter, 30 feet of man-made overburden overlies the natural land surface on Point Hennepin. This is a plateau consisting of the solids resulting from ponding of plant wastes mentioned in a preceeding paragraph. It is white and exceptionally fine, mostly less than 44 microns in diameter. Where freshly exposed on the walls of the collapsed craters, this synthetic sediment is strikingly stratified, resembling a lake clay deposit. Chemically, the principal constituents are calcium carbonate, calcium sulfate, and calcium hydroxide, plus silica and other insoluble impurities which were in the original limestone raw material used in the chemical operation that produced the waste. The waste sediment was transported to the ponding area in a liquor of calcium and sodium chlorides; and films of residual liquor containing these dissolved salts remain with the microscopic particles. Because of the extreme fineness of grain this man-made overburden is practically impermeable, preventing the washing out of the chloride liquor. The waste bed material is also relatively insoluble, being the inert product of a wet process chemical operation.

Below the tailings is about 60 feet of glacial drift beneath a thin veneer of organic marsh soil. The drift is a part of the Grosse Ile moraine, consisting of clay picked up from ground moraine by advancing ice and pushed into ridges on which erratic boulders were dropped (Sherzer, 1913, p. 290). There is no record of any continuous stratified sand or gravel within the glacial drift on Grosse Ile; the drift layer serves as a seal for vertical migration of ground water.

The top of the bedrock is at an average depth of 60 feet below the tailings. Although the older maps show Dundee Limestone to be present beneath the drift in this area, a recent manuscript map prepared by the late Erwin C. Stumm places the nearest subcrops of the Dundee a little over a mile away on the mainlands both to the east and the west. The top 155 feet of rock in this area belongs in the upper part of the Detroit River Group; strata of Detroit River age are exposed on Stony Island off the east shore of Grosse Ile and, beneath the Dundee, in the Sibley Quarry on the mainland to the west. They consist mainly of impure dolomite.

Below the Detroit River carbonate rocks is the Sylvania sandstone, also a part of the Detroit River Group. The Sylvania is the exploited glass sand resource of Michigan. The cementation is from tight to moderate. The Sylvania is the lowest unit in the Detroit River Group (Landes, 1951). On northern Grosse Ile (Point Hennepin) it is approximately 140 feet thick. Two dolomite beds occur near the base.

WYANDOTTE CORE HOLE NO. 2; NORTHERN GROSSE ILE

FEET	LOG	REMARKS

DEPTH

- 0
- 100
- 200
- 300
- 400
- 500
- 600
- 700
- 800
- 900
- 1000
- 1100
- 1200
- TD 1326

Plant Waste

Glacial Drift (moraine) clay and boulders

Detroit River Dolomite

Sylvania Sandstone

Bois Blanc Cherty Dolomite

Bass Island Dolomite

G

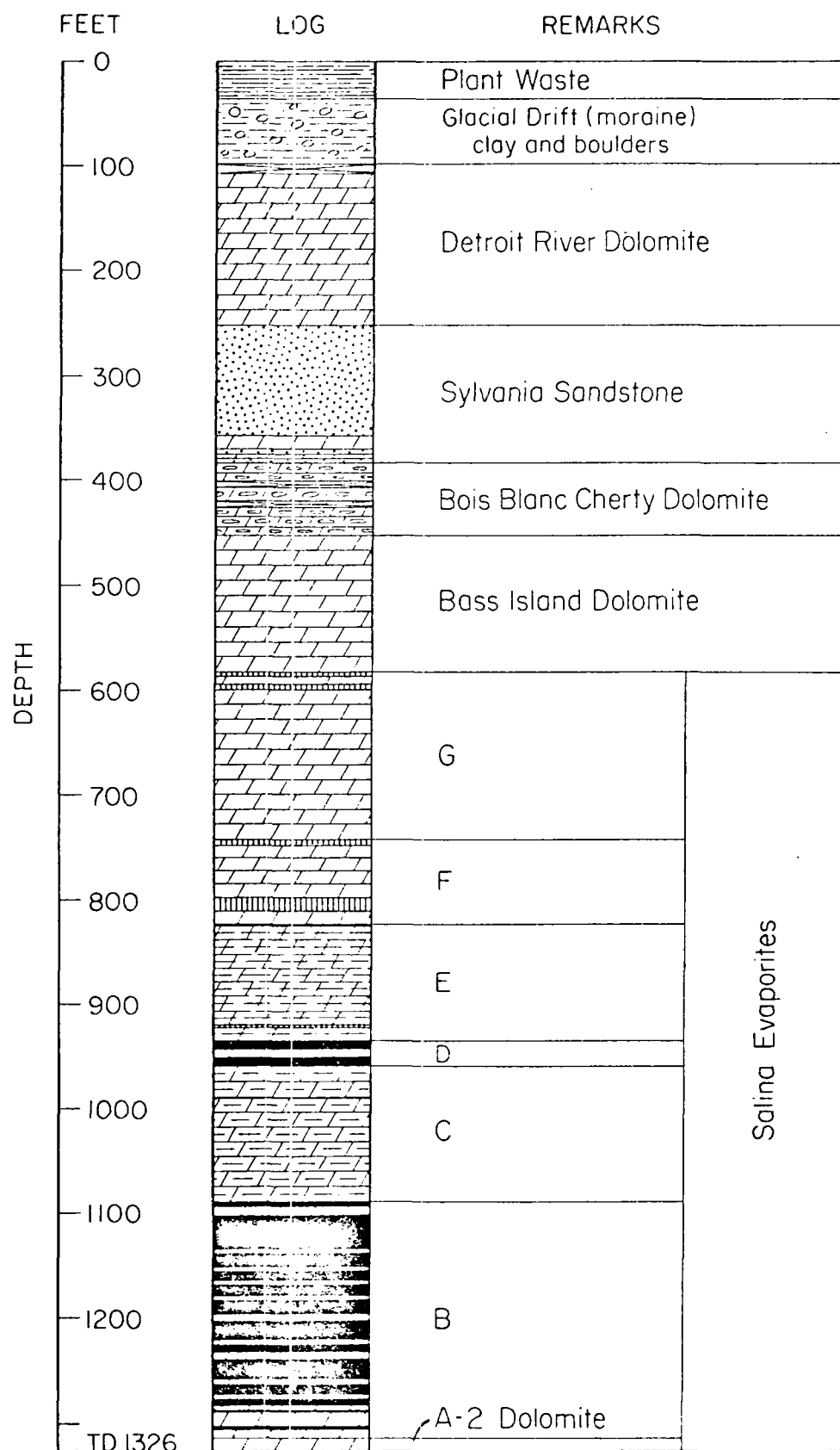F

E

D

C

B

A-2 Dolomite

Salina Evaporites

Figure 3
Typical core log of Hennepin Point brine field. Solid pattern shows salt beds, vertical lines designate anhydrite layers, rhombic bricks are dolomite, and the flattened circles represent chert nodules. Unit E is dolomitic shale and Unit C is shaly dolomite; both contain some anhydrite and salt.

Next downhole is the Bois Blanc Formation, which contains the lowest rocks of Devonian age in this area, consisting of 62 feet of cherty dolomite. The underlying upper Silurian rocks are in the Bass Islands Group; they consist of impure non-cherty dolomites, mostly gray in color, and 135 feet in thickness.

The salt measures lie within the Salina Group which underlies the Bass Islands rocks. The Salina has been penetrated through a thickness of about 730 feet on Point Hennepin; this includes all of the salt beds in the area. The Salina Group has been subdivided into units G to A (Lances, 1945). The major salt beds here are confined to the F, D, and B units, but in other parts of the Michigan salt basin salt beds occur in the A division as well. The vertical distribution and thickness of the salt beds can best be seen in Figure 3. The salt now being exploited by BASF Wyandotte Corporation lies in the B unit. Accompanying the salt as interbeds are layers of rock ranging in thickness from a few inches to several feet. These layers consist of shaly dolomite and anhydrite with an appreciable percentage of salt. The G, E, C, and A units consist of, in decreasing order of abundance, dolomite, shale, and anhydrite; they also contain appreciable salt, making them subject to some leaching.

Mineral resources. The only mineral resources between the surface and the salt on Point Hennepin apparent at this time are glacial clay, dolomite, and glass sand, and none of these are workable here in our opinion. Clay is exploited elsewhere in Wayne County, which is second in the state in clay production, but on Point Hennepin it lies below river level. In addition, it is covered by 30 feet of ponded tailings, putting it to a significant economic disadvantage. The dolomite is impure, and too deep for strip mining. The glass sand, which is quarried on the mainland to the southwest, is also too deep here (top about 250 feet below the surface) for open pit mining and in addition it is covered by about 155 feet of hard and impure dolomite. Underground mining of the glass sand is unlikely, for this porous and permeable rock crops out in the bed of Detroit River off the southern end of Grosse Ile so any mining activity would be subject to being flooded out.

Structural geology. Grosse Ile lies high on the southeastern flank of the Michigan basin, a near circular downwarp of the earth's crust that has been filled above the Precambrian floor by a maximum of about 14,000 feet of sedimentary rocks, including the Salina salt section of Silurian age. The depth to the Precambrian floor beneath Point Hennepin is about 3600 feet. The rim of the basin, proceeding clockwise from the Algonquin arch, which is the backbone of the southwestern Ontario peninsula, runs southwesterly along the Findlay arch across western Lake Erie and northwestern Ohio, and thence northwesterly following the Kankakee arch in northern Indiana and in Illinois. From there on the trend of the rim is northerly, easterly, and then southeasterly along the Precambrian edge in Wisconsin, the northern peninsula of Michigan, and southwestern Ontario. The center, and deepest part, of the basin is in Clare and Gladwin Counties, Michigan, west of Saginaw Bay. The average basinward dip on the top of the Precambrian floor in this area is about 80 feet per mile, but the dip lessens up the stratigraphic column so that at the level of the Silurian and Devonian rocks that are involved in this report the average dip is about 50 feet per mile. The average direction toward the center of the basin in Wayne County is north-northwest.

Inevitably, the regional pattern of uniformly dipping beds is modified locally by minor folding and by temporary emergences during the geologic past that brought about thinning and even removal by erosion of some of the sedimentary layers. These are described in subsequent paragraphs.

An unpublished map of Essex County, Ontario, prepared by P. L. Garvey (1941) shows minor anticlines and synclines at the top of the Niagaran, which underlies the Salina salt measures. The axes have a west-northwest trend which no doubt carries these folds across Grosse Ile. An upfold crosses the Detroit River and Grosse Ile at the latitude of Stony Island, and has been referred to as the "Stony Island anticline". This fold is succeeded to the north by a slight downfold (syncline) which, although the keel is rising to the west, probably crosses northern Grosse Ile. As a result of these local creases on the flank of the basin, and especially the Stony Island anticline, the local dip at the base of the B salt on Point Hennepin is northerly at about 65 feet per mile.

An extremely local structural and erosional feature completely blocks out the B salt between the North and the Central Galleries of the Point Hennepin brine field. It is shown on the B salt thickness map (Figure 4). This local interruption in the continuity of the B salt layers has been described by Jaron (1966). It is interpreted to be a solution collapse structure concurrent with deposition of the B and C units. The B unit, containing about 200 feet of salt, apparently was removed by circulating water soon after deposition and replaced through "bulking by collapsed insoluble ledges in the B salt section and approximately 50 feet of overlying unit C roof rock, plus a thickened undisturbed unit C dolomitic shale-anhydrite section, which accounts for the volume of salt removed" (Jaron, p. 422). As a result of this solution and collapse during Salina time the B salt is discontinuous beneath Point Hennepin, physically separating the North and Central galleries.
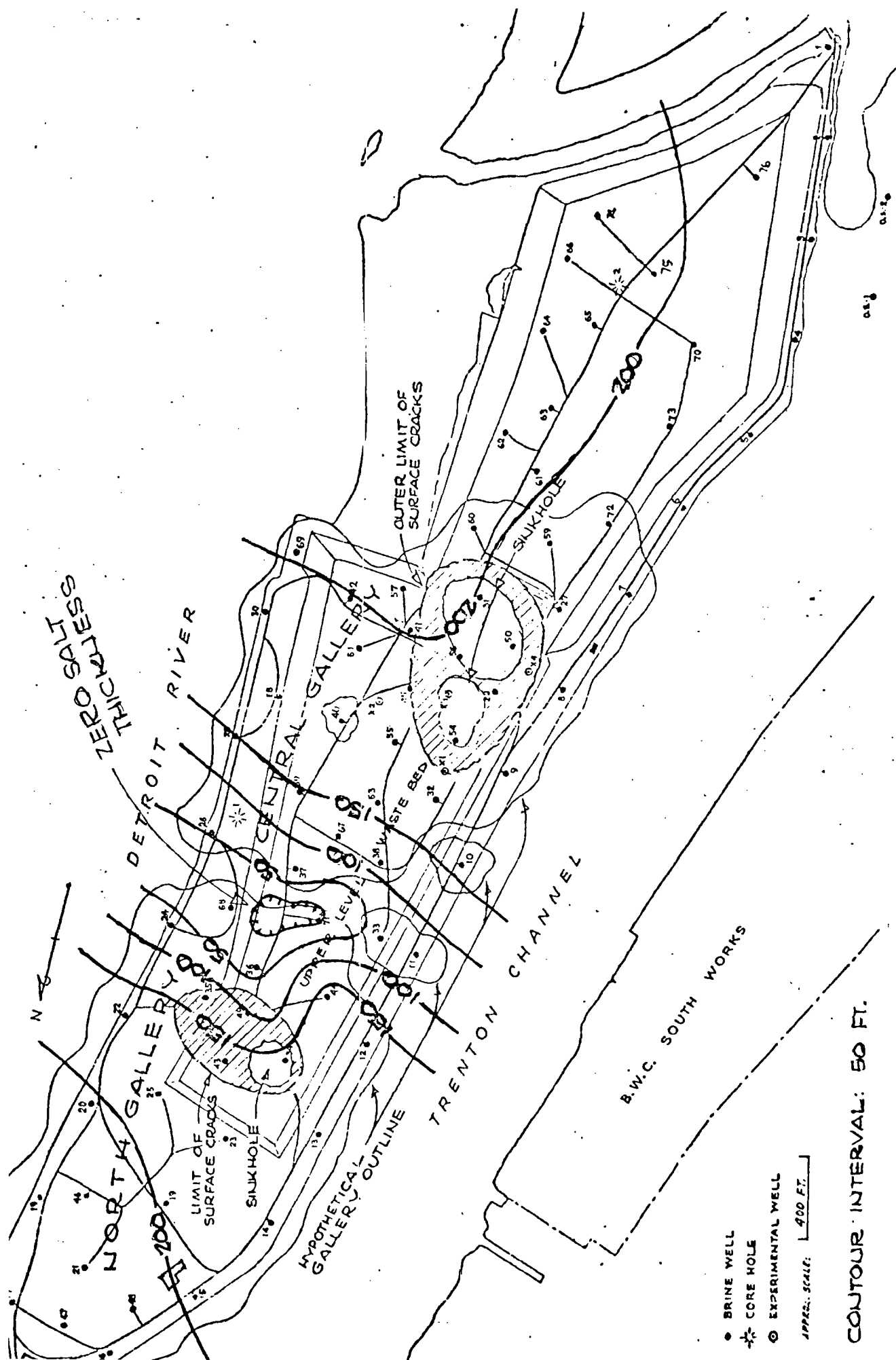
FIG. 4 – THICKNESS CONTOURS "B" SALT

COUTOUR · INTERVAL: 50 FT.

APPRX. SCALE: |___400 FT.___|

- • BRINE WELL
- ⚬ CORE HOLE
- ⊙ EXPERIMENTAL WELL

ZERO SALT THICKNESS

DETROIT RIVER

NORTH GALLERY

CENTRAL GALLERY

OUTER LIMIT OF SURFACE CRACKS

SINKHOLE

LIMIT OF SURFACE CRACKS

SINKHOLE

HYPOTHETICAL GALLERY OUTLINE

UPPER LEVEL

WASTE BED

TRENTON CHANNEL

B.W.C. SOUTH WORKS

N

GROUND WATER

Free water. By definition, free water underlies the surface and is not under head. There is no free water within the tailings overburden on northern Grosse Ile because of the inadequate permeability of this material. The first water elsewhere on Grosse Ile occurs in the thin swampy soil zone at the top of the glacial deposits. This is approximately at river level, and the volume is insignificant because of limited storage capacity.

Confined (artesian) water. This water is under head because it is confined by overlying impervious rock. The uppermost confined water zone is at the top of the bedrock where a soil veneer, but especially an intersecting pattern of joint cracks, supply the necessary access for recharge. The sealing (confinement) is due to overlying impermeable clay. Joint cracks in the bedrock occur in the outcrop belt under the Detroit River; the head is thus the level of the river.

Below the zone of water-filled joint cracks in the bedrock are permeable layers. Some have intakes in nearby outcrop areas 10 to 20 feet above river level. These, when penetrated by a bore hole, produce flowing wells. The best groundwater records in the area were obtained prior to and during the sinking of the shaft at the Ojibway salt mine, 5 miles upriver from northern Grosse Ile and on the Canadian shore (Figure 2, locality 4). First a center hole was drilled and a formation log and water data were obtained. Before sinking the shaft the surrounding area was frozen to a depth of 350 feet in order to avoid water flooding and hydrogen sulfide gas poisoning problems. As the shaft was dug the aquifers down to 350 feet were prominently visible as rings of solid ice on the shaft wall.

It was noted in the Ojibway shaft that all of the water beneath the drift (at 87 feet) down to 710 feet was under sufficient aggregate head to overflow the surface pipe at approximate elevation 580 feet, or 10 feet above river. However, at 710 feet depth, where another vein was tapped, the pressure diminished so that the static level dropped to elevation 553, 17 feet below river. It is curious that no aquifers were specifically recorded in the Sylvania sandstone at depths 350 to 430; on the contrary it is noted that 120 gallons per minute were flowing downhole at 365 feet depth. Evidently the Sylvania is undersaturated here, constituting a "thief" zone.

A quite dissimilar condition was found about 7 miles downstream near the southwestern corner of Grosse Ile where the J. Swan well was drilled in 1903-1904 (Fuller, 1905). A log of this "Wonder Well", as it is known locally, is appended. The only water veins recorded in the entire log are a flow in sandstone at 420 feet and a much larger flow, 4,320,000 gallons per day, of sulfur water at 450 feet. The Sylvania sandstone should be about 200 feet thick here, which would put it between 300 and 500

J. Swan Well

Location: C NE¼ SE¼ section 31, T. 4S., R. 11E
           In southwestern part of Grosse Isle just opposite
           Snake Isle and about 3/4 miles from southern point
           of island.

Elevation: 576 feet above sea level from topographic map.

Record compiled from Pub. 12, Pub. 14 and samples by R. B. Newcombe
in 1928. Well drilled in 1903-1904 for oil and gas by Judge James
Swan.

	Thickness (feet)	Depth (feet)
PLEISTOCENE:		
Drift:		
Drift	17	17
DEVONIAN:		
Detroit River:		
No record (white to buff cherty and sandy dolomite at 300)	283	300
DEVONIAN-SILURIAN:		
Sylvania-Bass Island:		
Sandstone (flow of water at 420)(much large flow of fresh water with sulphur odor 4,320,000 gallons in 24 hours at 450)	70	370
No Record	1008 (1078)	1378
Silurian:		
Salina:		
No record (gray dolomite and red shale at 1378)	22	1400
Dolomite, light brown, chalky	100 (122)	1500
Niagaran:		
Dolomite, bluish buff	50	1550
Cataract:		
Shale, greenish gray and purple (Cabot Head member)	100	1650
Dolomite, buff to white, (Manitoulin member)	50 (150)	1700
ORDOVICIAN:		
Cincinnatian-Trenton:		
Shale, greenish gray (some buff dolomite from above)	10	1710
No record	7	1717
Shale, red	58	1775
Shale, gray to red, and dolomite, shaly	31	1806
Dolomite, pink and shale, greenish gray	21	1827
Shale, gray	46	1873
No record	502 (675)	2375
	TOTAL DEPTH	2375

feet in depth. This well is now flowing at an estimated rate of about 1 million gallons per day, and the sulfur water is allowed to continue to flow into the river.

Possible water in the salt measures. The salt, and associated layers of anhydrite and shale, occur at depths below 800 feet on Point Hennepin. These earth materials are slightly plastic at such depths, due to the weight of the overlying rock. This plasticity inhibits the presence of fractures that would permit water to penetrate the otherwise impermeable rock. Therefore, there is no naturally occurring water in the salt measures, and therefore no natural brine. The water in the salt beds today was introduced from the surface through wells drilled for the purpose of dissolving salt for commercial use. Salt gallery brine is near saturated, and 20% heavier than pure water. When a well cavity is abandoned it is full of brine and remains full. The brine becomes super-saturated in a short while in accordance with bottom hole temperature and pressure, and since water cannot get into the full cavity, there is no further dissolving activity. Furthermore, due to its high density, the brine cannot migrate out of the cavity to be replaced by water; therefore the dissolving mechanism becomes arrested upon termination of the operation of a brine cavity.

Quality of water in the overlying sediments. In a report on the water quality in the nearby Rouge River basin, Krutilla, (1971, Sheet 2), makes the following statement: "Water from bedrock is objectionable in nearly all quality aspects, and water obtained from formations older than the Antrim Shale is almost always unpalatable and is unsuited even for livestock use. In general, mineralization of water increases in depth, whether in the drift or bedrock". The same general conclusion applies to bedrock water beneath northern Grosse Ile, where the Antrim Shale has been eroded off. The bedrock water here is either too sulfurous or too highly mineralized and too corrosive to be usable either domestically or industrially.

GROSSE ILE BRINE OPERATIONS

Introduction. Salt is produced in the form of brine by a technique known as solution mining; the product is referred to as artificial brine to contrast it from naturally-occurring fluids containing soluble minerals. Sodium chloride brine is used as a raw material in the manufacture of certain chemicals based on the sodium or chlorine content. This is usually done by treating the brine; very little chemical use involves evaporating the brine to salt. As mentioned in the section on geology, the principal salt bed in the area, the Salina "B" unit, is approximately 200 feet thick in the Grosse Ile area and occurs at depths of 1100-1300 feet. The bed is essentially flat with a slight regional dip to the northwest. Interbedded in the salt member are layers of relatively insoluble anhydrite, shale, and dolomite impregnated with salt, ranging in thickness from partings to corre-latable units as much as 10 feet thick. These insoluble beds introduce operating problems in maintaining the salt well, for they collapse upon being undermined by dissolution of the salt.

A salt well typically is created by drilling a hole to the salt and introducing a string of pipe known as casing that is sealed in the hole by pumping cement into the annular space between the pipe and the drill hole wall. The cement serves both as mechanical support for the pipe and as a seal preventing the loss of fluid from the salt cavity. In a typical operation, water is pumped into the well which dissolves the salt and the resulting solution is removed either through a string of tubing introduced into the well or out an adjacent well, provided that a connection has developed between the two wells. As dissolving progresses, insoluble beds are undermined and eventually collapse. This collapse occurs (1) due to removal of the underlying support, (2) dissolution of the soluble minerals that may constitute the matrix of the layer, and (3) inherent structural incompetence. Structural incompetence may be due to weaknesses resulting from original deposition on the sea floor, the weight of subsequent overlying deposits, or stresses created by movements of the earth's crust.

The collapsed material accumulates in the cavity as rubble or debris usually stacked in a random fashion, and the resulting increase in volume is known as bulking. Collapse of a layer of significant thickness and its subsequent fall through the cavity frequently breaks or disrupts the pipe hanging in the well, causing an interruption in production. Collapse and pipe breaking are responsible for most maintenance expense and unreliability in salt well performance. Therefore this has been the principal area of investigation into improvement of salt well efficiency.

There are two techniques used today in brining: (1) the traditional or "conventional" method; and (2) the "undercut" method. The latter has largely superseded conventional brining except in salt domes where the salt deposit is both massive and unusually pure, and collapse of insoluble layers is not a problem. Descriptions of both types of solution salt mining follow.

Conventional wells. Wells for the production of salt by the artificial brine method of solution mining evolved from technology available toward the end of the nineteenth century, which was a combination of water well and oil well practices. Brine wells were drilled by contractors using oil field techniques and materials. Casing was set at the top of the salt, and a string of tubing lowered to the bottom of the salt section to be brined.

This method of operation, wherein water pressure at the surface provides the energy to lift the resulting saturated brine back to the surface, is referred to in England as "forcing". Forcing requires a pressure-tight cavity, a condition usually prevailing in the early life of a well. It was soon learned that introduction of the feed water down the casing annulus ("casing injection") produced brine at a high efficiency because the system was operating by gravity segregation wherein the fresh water was floating on the top and the dense brine was being removed from the bottom. It was also found that this method caused the highest rate of salt extraction at the top of the cavity immediately under the roof, resulting in roof collapse early in the life of the well with attendant problems of tubing failure and repair expense. Due to greater dissolution of salt of the top of the cavity, where lighter undersaturated water accumulated, the cavity in near horizontal beds developed a conical or morning glory shape. In time the fringes of the morning glories in adjacent wells would coalesce at the top. The connection thus established permitted circulation from one well to another. The longer path improved well efficiency; it also undermined large areas around the wells. It was noted that if the strata were inclined dissolution would advance more rapidly updip beneath the insoluble roof producing an eccentric morning glory shape. This has been demonstrated both by modeling experiments and by actual cavity surveys made in recent years.

It was determined later that introduction of water in the tubing and production of brine from the casing annulus, or where wells had coalesced, from the tubing of an adjacent well, causes the flow in the cavity to be countercurrent to gravity segregation. This produces mixing in the lower section of the cavity and prevents the fresh water from reaching the cavity roof. As a result less dissolving of salt takes place in the upper part and more in the lower part of the cavity, and in consequence the cavity is less cone shaped and more nearly cylindrical.

Undercut wells. Early brine technologists investigating problems of salt production in bedded salt containing interbedded layers of insoluble rock concluded that the problem could be eased if two wells could be connected at the bottom of the salt bed. Such a connection would allow water to flow from the input to the output well, dissolving salt along its path. Layers of insoluble rock exposed on the roof of the tunnel would fall to the floor, permitting continued dissolving of the salt upward. The collapsed interbed rubble would accumulate in the area between wells and therefore not interfere with the well casing and tubing.

Wells were connected by undercutting in the 1930's using an immiscible medium such as air, introduced in the well to float against the salt roof, thus preventing upward dissolving and forcing lateral dissolving. This immiscible material is known as a "pad"; air was succeeded as a pad by oil and other lighter than brine substances. The undercut

-18-

method soon demonstrated its efficiency and value. Later, following the development of hydraulic fracturing by the oil industry, this technique became common procedure in salt brining. Hydraulic fracturing is accomplished by forcing water under high pressure down a brine well and into the salt. If the hydraulic pressure forces its way laterally through the salt to a second brine well, the water following this fracture dissolves a conduit, which enlarges into a flow channel, thereby soon permitting the operation of the input well at normal well-head pressure.

Effects of purity and structure on the dissolving of bedded salt. It is axiomatic that the less pure salt layers, a mixture of salt and insolubles, will lag behind in the dissolving process. Eventually the interbedded anhydrite and shale will accumulate on the cavern floor. Interbeds with minor amounts of salt, consisting of anhydrite, shale, or dolomite, or blends of these materials, will not dissolve and will provide false floors and roofs until solution of the underlying salt results in collapse by fragmentation of the insoluble layer.

In its movement through the cavern, from feed well to production well, whether these be concentric casings in the same hole (conventional wells), or separate but cavern connected wells, the water increases in salinity by solution of salt. The most solution will take place at the top of the cavern where the freshest and lightest water accumulates. Laterally the deepest penetrations into the wall rock will be in the layers that are most soluble due to purity and granularity. This differential solution over long periods of time has been seen to produce tongue shaped openings, sandwiched between false hanging and foot walls, that extend for considerable distances beyond the main cavern. Furthermore, the greatest dissolving activity, other conditions being equal, takes place updip, even though that dip may be but a few tens of feet per mile. This is because the fresh water is forever rising above the more saline water, seeking an impermeable barrier, which is either the hanging wall or a false hanging wall, and then moving updip beneath this barrier. At the same time the saturated brine slides down dip beneath the fresher water to the main cavern where it seeks the lowest level possible.

Grosse Ile brine production. Brine wells were drilled on Grosse Ile starting in 1943 and operated by the conventional method as single cavity wells, which later coalesced into two major galleries (North and Central) and additional minor galleries (Figure 5). Due to the absence in those days of cavity measuring devices and remote sensing instruments for measuring and reporting conditions in the subsurface, the early ideas of cavern geometry were largely inferred. Coalescences were detected when changes in the flow of one well would affect an adjacent well. When this occurred operations were usually rearranged to accommodate this change in flow pattern in order to optimize production efficiency.

With the development of undercutting techniques, wells were drilled in the intervening space between the wells in the gallery, usually on an equidistant basis, and completed and developed by hydraulic fracturing. It is interesting to note that frequently the salt bed would be found to be intact at this intermediate location, indicating the erratic character of coalescence of conventionally operated wells. Development of offset undercut wells permitted the abandonment of conventional wells. This improved both operating efficiency and eliminated the repair expenses required by the conventional wells.
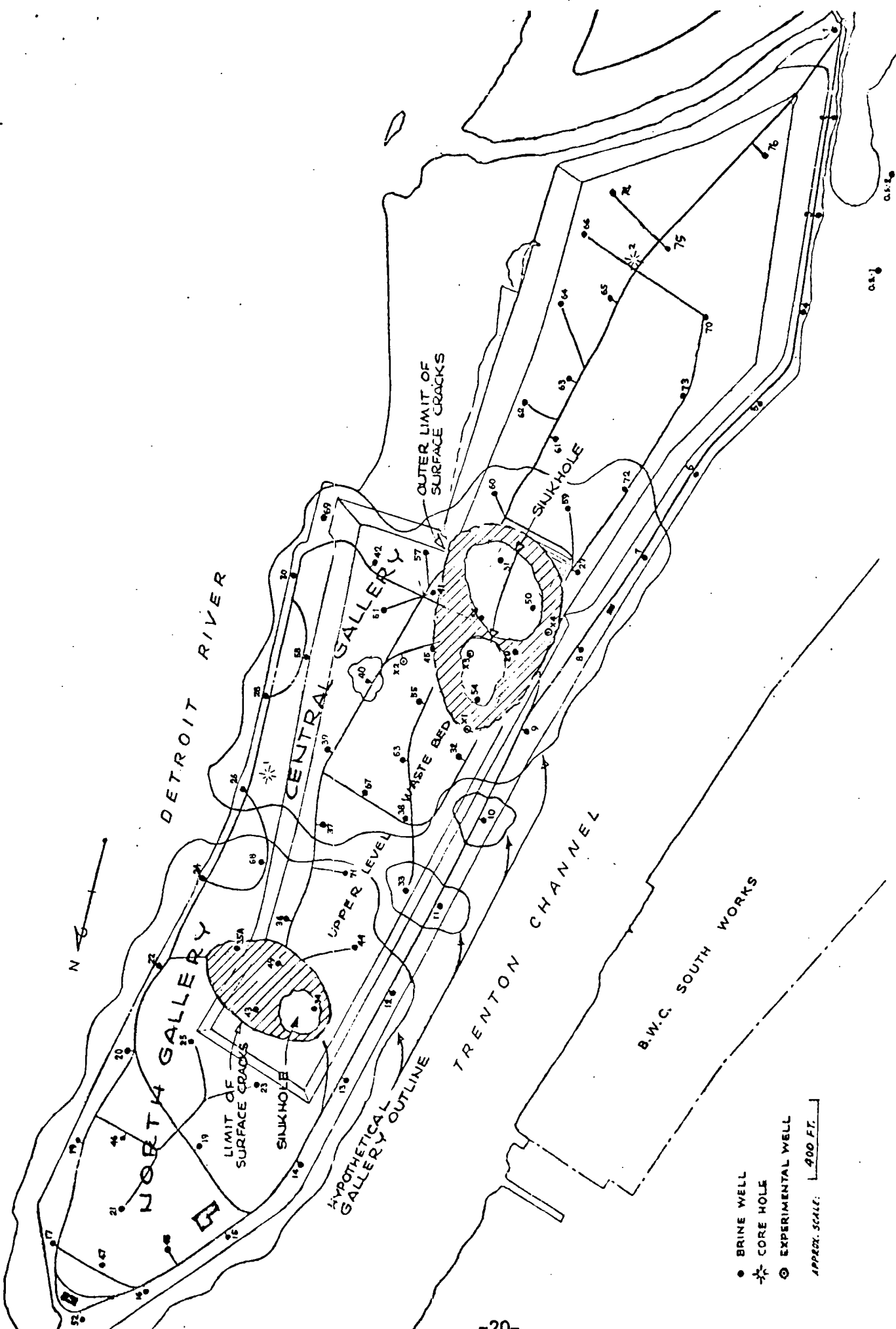
FIG 5. GROSSE ILE BRINE FIELD

BRINE WELL
CORE HOLE
EXPERIMENTAL WELL

APPROX. SCALE: 400 FT.

DETROIT RIVER

NORTH GALLERY

CENTRAL GALLERY

SINKHOLE

WASTE BED

UPPER LEVEL

LIMIT OF SURFACE CRACKS

SINKHOLE

HYPOTHETICAL GALLERY OUTLINE

OUTER LIMIT OF SURFACE CRACKS

TRENTON CHANNEL

B.W.C. SOUTH WORKS

N

Figure 6 shows by bar diagram the salt dissolved by the feed wells in the North and Central Galleries. The length of the bar indicates the relative volume.

Early indications of subsidence. As discussed above, operation of conventional wells is recognized to cause undercutting of large areas at the top of the salt beds beneath the overlying rock that constitutes the roof of the cavity. Early indications of undercutting were obtained when wells were found to have coalesced at the top, permitting essentially fresh water to pass from one well to another; because of the low gravity of the produced brine, it was assumed that this connection was across the roof or even in the overlying rock through bed partings. Additionally, some wells drilled near conventional wells encountered cavities at the top of the salt bed. Another result of the operation of conventional wells was progressive caving or stoping, to use a mining term, of the overlying layered rocks surrounding the well casing. This was determined by collapse or loss of casing, and the introduction of the wireline caliper device showed loss of roof rock that had taken place in the interval between logging runs. Collapsed material was found to be accumulating on the cavity floor by either sounding line or measurement of the depth at which drilling tools or tubing hit the top of the rubble pile. In many instances the increase in volume of the rubble, due to random stacking of collapsed material, caused the rubble pile to grow near to or up to the new cavity roof. This mechanism, known as bulking, is considered to have filled the void in many places, and restored support of the overlying rock, thereby preventing further collapse. Roof collapse was one of the factors contributing to a decision to abandon operation of a salt well. It is important to note that these observations could only be made in the immediate area of a well, and much cavity development could conceivably take place elsewhere undetected.

Where large areas have been undermined by salt brining at depths of less than 3000 feet, downwarping of the surface sometimes takes place. The downwarped area reflects the unsupported cavity roof, and can be delineated by precise level measurements of elevations of reference points on the surface. Reference point elevations were taken on the Point Hennepin brine field starting in 1954, and since that time areas of settlement were mapped over the two major galleries. A typical contour map of settlements over two-year period is shown in Figure 7.

Analysis of the data indicates that settlement in a specific area can be retarded by rearranging well functions, particularly discontinuing the use of feed wells in an area of active settlement.

Subsidences of 1/4" per year were considered to be acceptable in this area, and cumulative settlements of several feet over the entire parcel were also considered to be tolerable if the downwarping was uniform and did not result in tension breaks in buried pipe lines or other installations. Recognizing that the patterns of settlement produced by subsidence observations and volume of salt produced indicate a maturing situation, preparations were made for abandonment of production from the two major galleries and for transfer of salt operations to a new area. These were underway by mid-1970 and abandonment was scheduled for mid-1971. This schedule was considered to be consistent with observed settlements and was further substantiated by exploratory wells drilled in
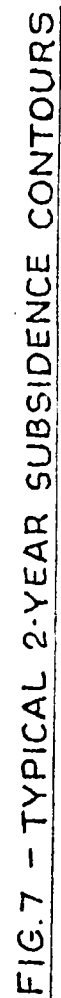
FIG. 6

BAR DIAGRAM SHOWING SALT PRODUCTION ATTRIBUTED TO NORTH AND CENTRAL GALLERY FEED WELLS. INDICATES RELATIONSHIP BETWEEN LOCATION OF FEED WELLS AND SINKHOLES.
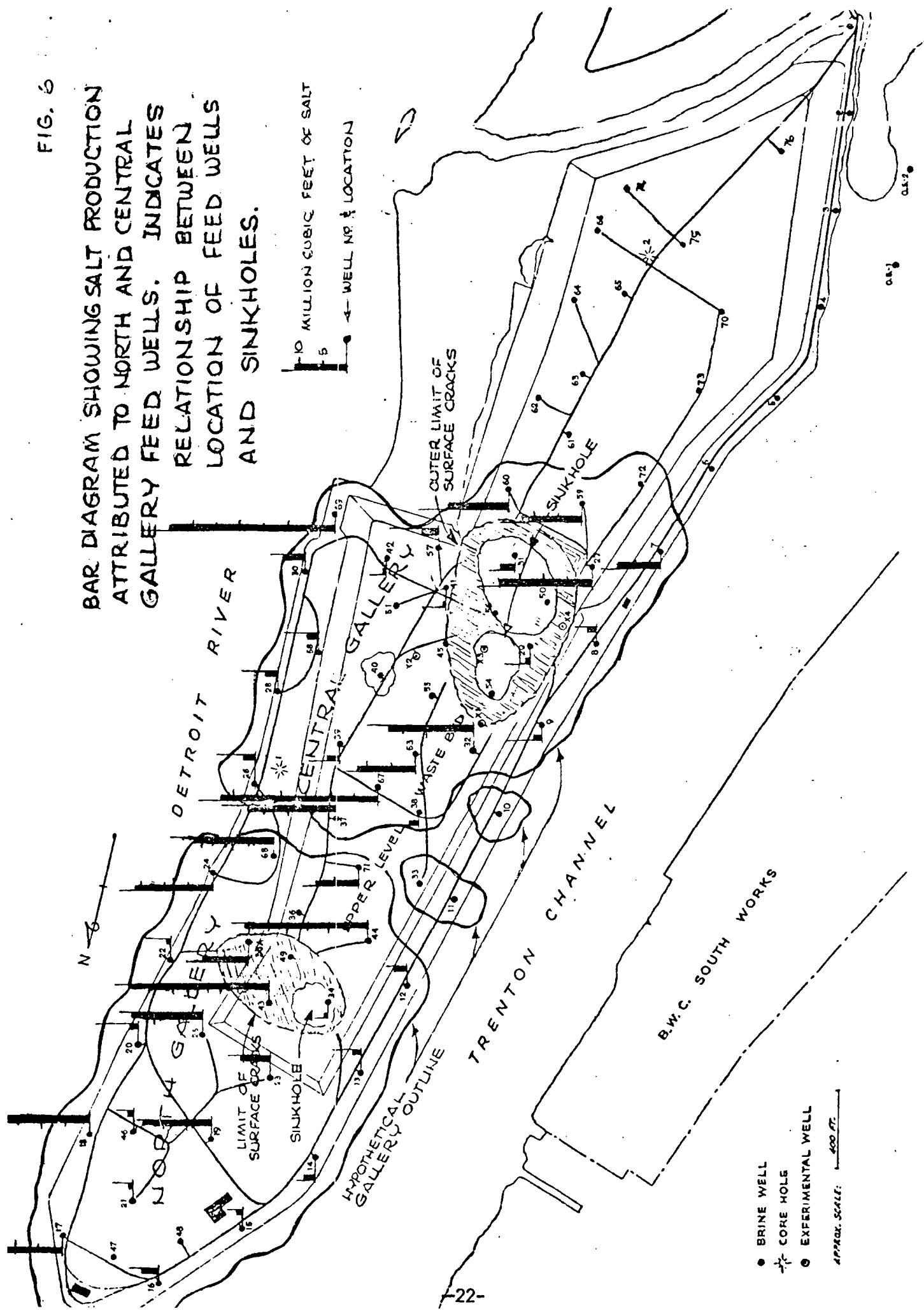
the area of major settlement that indicated no significant open cavity.

Other positive indications of response of the overlying rock to cavities in the two major galleries were breaks in the casing of certain wells at depths between 500 and 800 feet. These breaks were tensile in character, usually pulling apart at a coupling and rarely with any lateral offset, although in 1963 a break in the 8 inch casing of well 53 in the Central Gallery was observed by downhole television to be offset approximately four inches. A second manifestation was the observation in 1963 that the Central Gallery was no longer pressure tight, indicating that collapse of the roof had created a path into the overlying rocks giving access to the ground water regime. From this time on, the gallery was operated by means of submersible pumps in the producing wells and the feed water was metered to balance brine production. In the case of over-injection of feed water, the water table in the surrounding area could be raised, causing sulfur water to flow from shallow wells penetrating the veneer of clay that seals the bedrock water. In the event of underfeeding, water would be drawn from the ground water zone into the cavity to make up the differential between injected water and brine production. This was usually detected by the presence of hydrogen sulfide in the brine. A slight amount of overfeeding was normal practice in order to prevent induction of this sulfur water. Because of gravity segregation, the fluid driven upward from the cavity into roof rock by overfeeding is the least saturated in the cavity. Therefore it is unlikely that brine of high salt concentration enters the ground water zone immediately above the salt as a result of this practice. Even if this were the case, the brine would be expected to remain deep due to its greater density.

FIG.7 – TYPICAL 2-YEAR SUBSIDENCE CONTOURS

BRINE WELL
CORE HOLE
EXPERIMENTAL WELL

APPROX. SCALE 1 INCH = 400 FT.

-24

Theory of sinkhole formation. Sinkholes, both natural and man-made, have occurred many times in the past and are found in many areas of the earth's surface related both to natural forces and man's activities; all have one common cause, the removal of support. Sinkholes relating to salt production are not uncommon, but little was known as to the actual mechanism of the subsidence, or the optimum point at which extraction could be discontinued to prevent damage to the surface. An important factor is the contribution of the overlying rock section that is called upon to provide support above the salt cavity during and after removal of the salt by the brining operation. As mentioned previously certain effects, such as coalescence of the cavities over large areas and stoping of the roof around the wells, indicate the magnitude of the removal of roof support. Another indication is downwarping detected at the surface by precise level surveys.

However, surface downwarping can take place without cratering. For example, the original brine field of Wyandotte Chemicals Corporation at the North Plant on the mainland displayed surface settlement in certain areas (see Figure 8). Drilling and exploration in this field, after its abandonment, revealed no large open caverns but instead that the cavities were filled with rubble from floor to roof. These synthetic pillars created by bulking prevented the sinkhole mechanism from operating. Change in slope of the time vs. settlement plots (see typical example, Figure 8) indicates that subsidence was arrested upon termination of North Works brine production 1950-52. This change in slope has been observed at other brine fields upon termination of production; the mechanism is expected to operate on Grosse Ile as well.

When nearly horizontal rock strata are involved, roof failure (whether it be in a salt cavity, mine, or tunnel) starts with the separation and fall of an inadequately supported slab of rock. This exposes overlying layers, and one by one they follow suit. The mechanism involved is referred to as chimneying, for it results in a cylindrical break sequence similar to a chimney. In the case of salt brine galleries the chimneying takes place over the center of extraction. Where the rocks are competent, the area involved is smaller than the gallery. This is an important concept; simply stated, it requires the subsidence basin to be within the limits of the brine field.
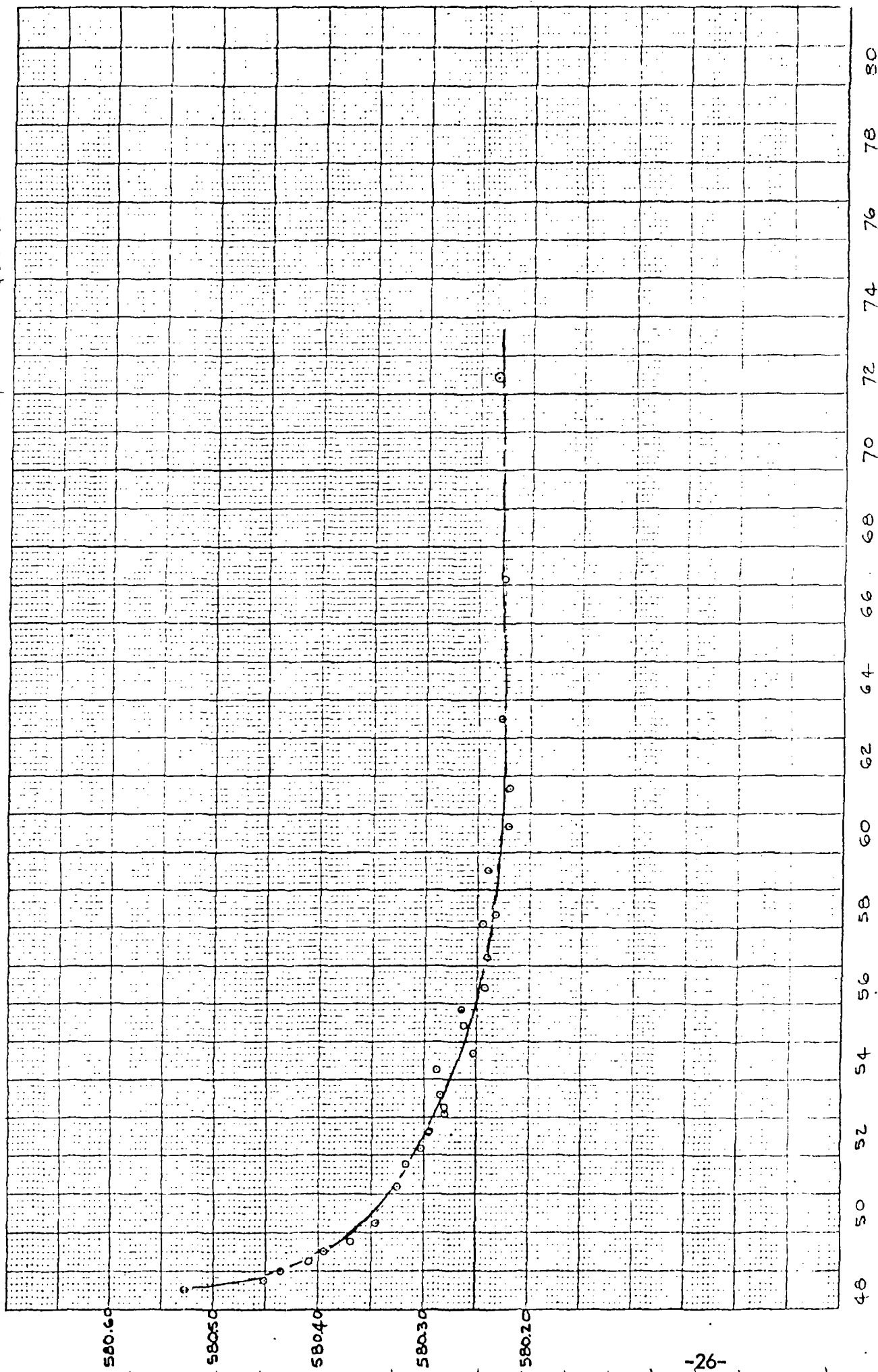
The stoping or chimneying mechanism involves change in position of the roof material and its transfer to the rubble pile. Assuming a cylindrical shape, and bulking, it is conceivable as described previously that chimneying will extinguish itself when the rubble pile consumes the available space created by removal of the salt, or reaches the angle of repose for this material. One important aspect of this mechanism is that material is changing position and the originally closely packed layered rock is being converted

FIG. 8

TIME VS. SETTLEMENT PLOT OF A TYPICAL NORTH WORKS REFERENCE POINT SHOWING CHANGE IN SLOPE AFTER TERMINATION OF BRINE PRODUCTION 1950-52

Wyandotte CHEMICALS CORPORATION

NORTH WORKS TECHNICAL DIVISION

NORTH WORKS S.R.P. C-9
1400 N - 400 W

Sponsored by: Solution Mining Research Institute and BASF Wyandotte Corporation

-26-

into a random stacked rubble pile. This chimneying or stoping takes place over a
long period of time undetected. Surface effects are noted when the chimney undercuts
the uppermost layer or mass of material and this plug drops, breaching the surface and
creating a crater or sinkhole. It is at this time, or slightly prior, that the characteristic
circular cracks appear on the surface. These appear in the air photographs (Figures 9
and 10). Also, tension effects may be noted, including pipeline failures and cracking
of other surface structures related to subsidence. Sinkholes are usually dated from the
time the plug falls.

Chronology of the North and Central Gallery sinkholes 1969-1971. Following
is a description of events observed in the field during the period starting with the first
surface manifestations in the area of the North Gallery and ending with the development
of the Central Gallery sinkhole. Well locations are shown in Figure 5, and Figures 9
and 10 present air views of the specific areas involved.

Generally, surface effects such as pipeline breaks and cracks were limited to
the North Gallery sinkhole, and these, in turn were confined to an area 800 x 1000
feet almost exclusively east of the sinkhole and 500 feet north and south of the centerline.
This area is outlined by the "Limit of Surface Cracks" (Figure 5) around the north sinkhole.
Within this line the surface sagged but did not actually collapse. Tension breaks in pipe-
lines traversing the area were the result of this gradual subsidence.

Both sinkholes had been delineated by areas of active downwarping as indicated
by contour maps based on precise elevation surveys made over several years. From these
readings, and exploratory work done in the wells themselves, it was concluded that
surface effects would be limited to several feet of settlement; the repairs described were
made with that in mind.

Other than subsidence shown by the precise elevation measurements, other
early manifestations were horizontal tension effects, notably pipeline breaks and surface
cracks, and vertical tension effects, chiefly casing breaks.

The Central Gallery collapse was not preceded by surface cracks or pipeline
breaks, or by development of a basin of subsidence prior to sinkhole formation.

North Gallery Sinkhole Area
1969

October. Operations were undertaken to plug well 43, which had been retired earlier.
Found casing parted at 260 feet, 370 feet, and 700 feet, hole was intact to
900 feet.

November. Several 1/4" cracks observed in the area of well 49. These cracks appeared
in the roadway, made of dense compacted material competent enough to crack.
These early cracks disappeared in the weak and softer material adjacent to the
roadway. The cracks were tensile in character, showing no recognizable vertical
offset, and were arranged circumferentially to the final depression. The early
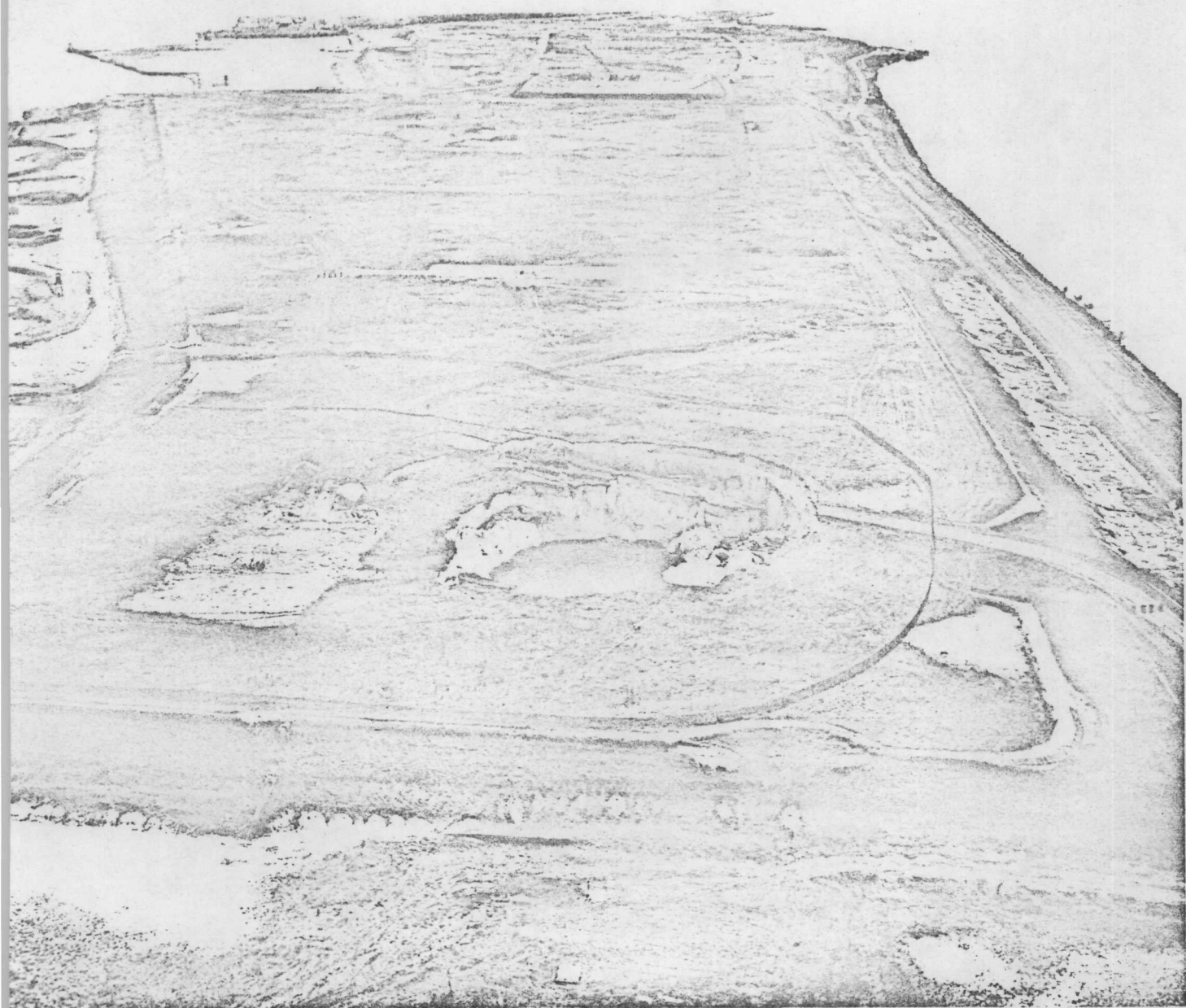cracks defined essentially the outer limits of the cracking.

Figure 9

View of north gallery sinkhole — Grosse IIe, looking south. Location of abandoned well 43 is at left center; casing of well 34 can be seen extending from right side of water-filled crater. Sinkhole is at right (west) end of an area outlined by surface cracks visible in the photo extending eastward in a roughly elliptical shape. Surrounding entire area is a snow fence, approximately 75 feet back from line of zero cracks. Sinkhole is at west end of disturbed area — no cracks are noted westward. Wells 71 (upper center beyond snow fence) and 44 (upper right center) were logged and found to be intact. Center gallery is at top of photo — abandoned brine reservoir, site of center gallery sinkhole at at top center.

Figure 10

View of Center gallery sinkhole looking south. Roadways and well sites of active (background) and abandoned (foreground) wells can be seen on the upper level of the retired waste bed. Water level in crater stands at river level. Waste material is semi-plastic, moist and chalky in character developing vertical cliffs where undermined. Satellite hole adjacent to center gallery sinkhole appears to be shallower, is included in line of zero cracks which encircles craters and includes broken ground northeast of main crater.

March 18. Tension break in buried 14" brine main near well 35A. This main, along with a 14" high pressure service water line and a 4" potable water line serves the east side of the island and passes through wells 25, 35A and 68. This area showed tension cracks early in the year (Figures 11 and 12). The leak was repaired with a compression sleeve.

March 23. Water main leak near well 25. Also a break reflecting tension in pipes buried in plastic material.

June 1. Repair sleeve pulled apart near well 35A.

July 24. Broken weld joint in a brine line near well 44.

October 5. Break in potable water line near well 35A.

October 22. Repair sleeve pulled apart near well 35A.

November 10. Surface cracks several inches wide in road near well 49 observed at 8:00 a.m. Increase noted in injection pressure in well 71 and rise in static fluid level in observation well 44 from a normal depth of 60-65 feet to 40 feet below grade (top of waste bed, 30 feet above river). Sulfur water flowing from casing of surface pipe at well 48 (elevation, 10 feet above river level). Smooth basin-shaped depression south and east of well 43 about 2-1/2 feet deep, 100 feet in diameter (Figure 13).

Ran caliper in well 71 and found casing intact to original depth. Ran sounding line in well 44; no change from earlier readings of 1181 feet.

November 11. Well 48 stopped flowing. Cracks concentric with depression adjacent to well 43 now show vertical offset of several inches as well as horizontal openings. Depth appears to be 10-20 feet, which is the depth of the competent waste bed material. Surface depression enlarging toward well 34; difficult to estimate because of soft soil and tall weeds covering the area.

November 12. Total settlement of well 43 area 6'-1" since reading taken in September.

November 20. Break in potable water line in area of well 35A.

December 4. Total settlement in well 43-34 area is 7'7". It is still a subtle basin with some step-like cracks 6" to 12" in size, with appreciable scarp. Outer limit of cracks well defined, not enlarging.

December 7. Brine main break in the area of well 35A.

December 10. Service water main break in well 35A area.

Figure 11

Closeup of cracks at well 34 looking east, defining the south side of the north gallery sinkhole. Very little vertical component of motion was visible at this stage.

Figure 12

View from well 34 down road toward well 49 showing cracks which developed in roadway, defining the south side of the north gallery sinkhole.

December 13. Drinking water line break in well 35A area.

December 16. Water main break in well 35A area. City water line break in same area.

December 18. Water main break opposite well 22.

1971

January 5. City water line break opposite well 22. City water line break south of
well 35A.

January 6. Calipered well 34; tool sat down at 166 feet, then fell off and bottomed in
open hole at 201 feet. End of 8" casing now at 193 feet.

January 7. Water main break south of well 35A.

January 8. Calipered well 44 bottomed at 1181 feet. Also ran neutron log.

January 9. Sinkhole approximately 25' x 30' appeared west of well 43 and about 150
feet north of well 34. Bottom of hole approximately 25 feet below original road
grade; vertical walls.

January 27. Sinkhole enlarged; water now filling bottom, equal to river level. Sulfur
odor.

January 29. Sinkhole enlarging; now exposing concrete pad adjacent to well 34.

February 5. City water line break south of well 35A.

March 3. Brine main break at well 35A. Isolated this section; will not attempt to repair
further.

March 4. Isolated section of water main passing well 35A in anticipation of its breaking
again.

March 11. Sinkhole enlarging; surface cracking south and west of well 34.

March 13. Concrete pad and piling at well 34 lost in hole; drive pipe and casing still
intact, standing unsupported at original height. Hole 25 feet deep adjacent.

March 24. Casing of well 34 settled about 3 feet below original grade. Area about 30
feet south of well settling into hole. Material starting to stack at the foot of the
walls (Figure 14).

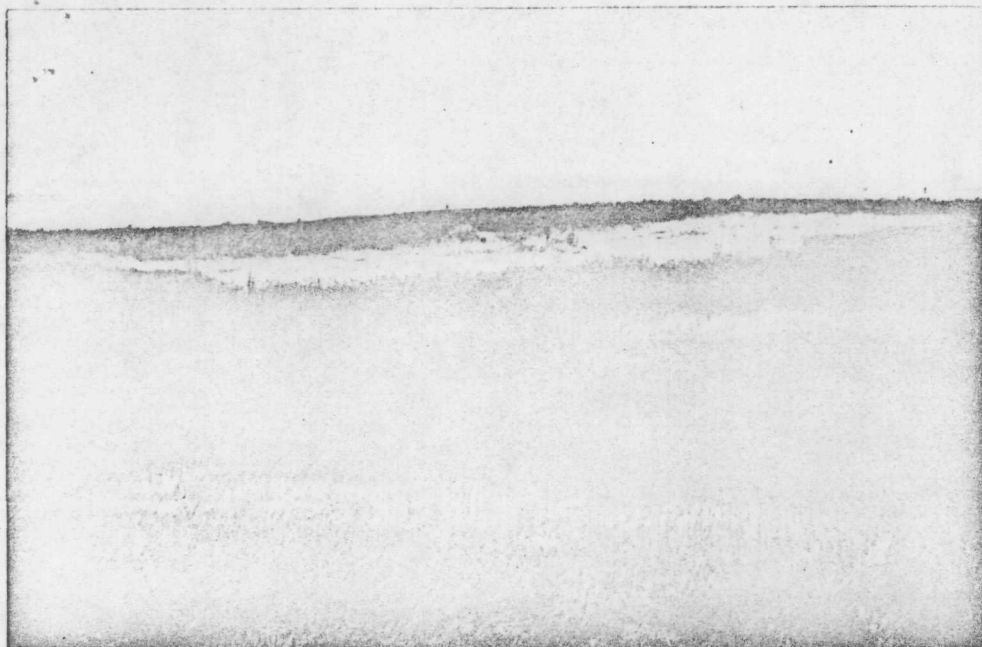March 25. City water line break south of well 35A.

Figure 13
View from well 34 looking northeast toward well 43, site of north gallery sinkhole, showing swale or depression which developed in previously-level terrain, representing the first or subsidence phase of the north gallery sinkhole. Formation of the crater occurred several weeks later.

Figure 14
Detail of north gallery sinkhole looking south showing broken ground slumping into crater. No cracks were formed south of the rim although a broken and slumped area was developed eastward. The casing of well 34 can be seen extending from the margin of the pool.

March 26. Well 34 drive pipe has settled another 4 to 5 feet. Also the area about 60 feet south of the well has settled several more feet. Cracks developing several feet back from the edge west and north of the present perimeter. The entire settlement area has now taken a roughly rectangular configuration running east and west about 60 feet south of well 34 and through well 49 and about 80 feet west and 180 feet north of well 34. It then runs eastward past wells 43 and 49 to about 120 feet east of well 35A. The sinkhole remains confined to the west end of the area of settlement.

March 29. Well 34 casing and drive pipe settled a few more feet.

March 31. Well 34 casing settled a few more feet; and also starting to tilt to the north.

April 6. Well 34 casing now down about 15 to 18 feet below original elevation.

April 8. Brine main break between wells 49 and 36.

April 12. Sinkhole crater developing eastward now within a few feet of well 43 subsided and broken ground extends eastward, includes east rim of upper waste bed. Well 34 casing now down about 20 feet below original grade and tilting north at about a 20° angle.

April 22. At this time operations were started to relieve the steep scarps constituting the north, west and south walls of the sinkhole proper by excavating the surface back from the crater and casting the material into the hole. The scarps were considered to be an undesirable safety hazard. The east area was too broken to permit access by excavating equipment. Water level stood at river level, and material could be seen to be stacking at foot of scarps. Depth was estimated to be 100 feet.

May 14. Additional minor settlement around wells 43 and 49 of the North Gallery. Area appears to be badly broken, with total settlement about 10 feet.

The North Gallery sinkhole subsequently stabilized and other than minor adjustment, has not changed since. Remote wells (46, 48, 68) were operated while new capacity was being developed. Pumping level of brine could be maintained at the normal 250 feet below grade. Level in observation well 44 returned to normal in 2 days after the events of November 10-11.

-34-

Central Gallery Sinkhole Area
1970

May. Noted influx of sulfur water into wells 51, 55 and X-2 of Central Gallery. Suspected casing breaks or corrosion leaks in sulfur water zone. Influx noted when feed water was out of balance with brine production. Other than subsidence observed by precise levelling of reference points, no other manifestation was observed, such as cracks or pipeline failures. This area of activity was entirely on the upper waste bed, thus any downwarping would result in compression rather than tension in early stages. The brine reservoir was out of service and not subject to regular observation. Settlement or cracking in that area would go unnoticed. Wells in the center of the Central Gallery were largely retired at this time, preparatory to retirement of the entire gallery, contributing further to failure to detect cracks, if any. It can be said that the Central Gallery sinkhole was not preceeded by extensive subsidence of an extensive area delineated by cracks and gentle downwarping as was experienced in the North Gallery. The area was traversed daily by departmental employees competent to note subtle changes in the terrain; none were reported.

1971

April 28. Sulfur water started flowing from wells 9, 29, 41, and 42. At 7:00 p.m. a developing sinkhole was discovered at the northwest corner of an abandoned reservoir located southeast of well 29. Within two hours the sinking area included well 50, parts of the reservoir dike wall on the west and north sides, and a segment of the reservoir floor about 100 feet in diameter.

April 29. The new sinkhole now includes the road to well 27, and two 14" mains that cross from well 8 to well 69. Hole is now about 200 feet in diameter. Fluid level is about 15 feet below original road grade. Sulfur odor. By late afternoon, the hole had enlarged to an ellipse about 400' x 150' with the long axis, northwest to southeast.

May 1. Lost east wall (except corners) and most of the north wall of the reservoir. The 14" brine valve near well 41 pulled apart westward.

May 2. New sinkhole still enlarging. Has extended east of the road running to the southeast gallery and has exposed the two 18" mains that serve the south end of the island. Also, the south wall is starting to slough off. Cracks in the road south of the reservoir wall are extending around to well 27 location. Also, cracks enlarging in the area of wells 41, X-2 and 45, and developing between wells 45 and 55.

May 7. New sinkhole has now taken in well 56, extending east of this spot several yards, and few feet of well X-4. The area between wells 29 and 45 is settling.

May 8. About a third of the south wall of the reservoir fell in this morning.

<u>May 9.</u> The 7" brine line servicing well X-2 broke north of the south crossover.

<u>May 11.</u> No. 29 well site and drilling foundation fell into hole. Wells numbered 1-42 were drilled from concrete mats 10 x 20 feet in size constructed as a cap on 6 pilings driven to bedrock. This mat served as a base for the cable-tool drill rig. The well is located in front of the mat about 3 feet. As the terrain subsided toward the sinkhole by sloughing of slices a few feet wide by several tens of feet long, the piling and the mat were exposed, as was the well casing. The piling and mat soon toppled because of lack of support for the large mass. The well casing remained for several weeks, subsiding slightly and eventually tipping inward. Note comments referring to well 34 in the North Gallery sinkhole, which performed similarly.

<u>May 12.</u> Crater developing eastward to 10 feet from rim of upper waste bed.

Area east and north of well 29 subsiding; appears ready to cave in.

<u>May 20.</u> Area near well X-3 settling.

<u>May 22.</u> Several feet additional settlement near well X-3.

<u>May 25.</u> Sinkhole developed in area of wells 29, 54 and X-3 approximately 200 feet in diameter. Appears to be a satellite to the Central Gallery sinkhole, separated by a low bridge or barrier 5-10 feet above water surface that now stands at river level. This second depression might be interpreted to be a separate hole, although both lie within an elliptical area bounded by the zero crack line.

<u>May 27.</u> Satellite hole enlarged west to 20 feet from west wall of upper waste bed. Cracks in ramp leading to upper level enlarging.

<u>May 28.</u> Tension break in 14" water main near well 8.

<u>May 29.</u> Discontinued operation of all wells in North and Central Galleries. Had been producing from margin of gallery while developing replacement capacity.

<u>June 1.</u> Casing of well X-4 broke off. Cracks wider in ramp leading from well 8 to upper waste bed level. General slumping of terrain inside of zero crack line.

Beyond this date stability appears to have resumed in both areas. The area of zero cracks has not extended and the zone of broken ground surrounding each sinkhole has subsided only small amounts. Collapsed material is seen stacking around the margins of the water-filled craters indicating self-filling by collapsed material. Soundings in the main Central Gallery sinkhole indicate a flat bottom and depths of 100-120 feet below water level. The North Gallery and the satellite sinkhole were considered to be too precarious for access for sounding. Aerial photos of the satellite show bottom to be relatively shallow.

ENVIRONMENTAL IMPACT ASSESSMENT

Depressions on the Earth's Surface are a Way of Nature

A depression is a hollow completely surrounded by higher ground. Without depressions we would have no lakes; rainfall run off would follow stream valleys to the ocean. The oceans themselfes occupy mega-drepressions on the earth's crust. There are various geological processes that create lake depressions, and man may do the same thing by building a dam across a valley.

This study is primarily concerned with depressions brought about by sagging or collapse of the surface due to man's activity. The collapse craters are referred to as sinkholes. Just as for every man-made lake there are many thousands of lakes resulting from natural geological processes, so every man created sinkhole is overmatched by many thousands of natural sinkholes. In other words, sinkholes are not only a definite part of our environment, but a very interesting and in places (i.e., Jamaica, to be discussed subsequently) spectacular feature as well.

The following discussion of sinkhole and other collapse features is divided into two categories: those caused by man's activity; and those created by acts of God. In terms of timing, the man-made features are obviously confined to recent history; and the actual collapsing has in many instances been witnessed. On the contrary, most act of God collapsing is prehistoric. This is not surprising, when you recall that all historic time is but a split second of geologic time.

Acts of Man

There are three major types of activity that may result in surface sagging or collapse: (1) solution mining; (2) underground mining; and (3) petroleum or water removal. The first two of these create underground caverns, which may not reach the surface. The removal of liquids in the subsurface may be accompanied by additional compaction of the rock layers and this in turn can result in surface subsidence.

Examples of Salt Cavity Sinkholes in Addition to Grosse Ile

Subsidence due to salt production is quite common, particularly around the older brine producing areas. Such subsidence is usually limited to subtle downwarping of the earth's surface measured in inches, and it is difficult to detect without comparing periodic elevation surveys. Subsidence related to salt production is almost always confined to the area of influence of the salt wells, and usually goes undetected.

Sinkholes and major subsidences related to brine production have formed over the years; some in remote or inaccessible areas have gone unpublicized. In areas where salt operations have a long-established history, subsidence is accepted as a natural happening of minor importance. Following is a list of some of the more important examples.

Cheshire, England. The Cheshire area of England is perhaps the classic case. Salt occurs at shallow depths accessible to ground water; the resulting natural brine was produced as far back as history records. Water flowed in to replace the brine being produced and the resulting uncontrolled solution at shallow depth caused the creation of subsidence troughs over wide areas.

Salt mining in Cheshire was started in 1682. Many of the early mines were flooded and the workings converted to brine production. Extension of the area of extraction and dissolution of the mine pillars caused collapse of the mines and cratering of the surface.

Although modern techniques are now used for production of salt in Cheshire, subsidence is recognized as a natural occurrence related to this work. An excellent treatment of this subject has been published (Male, 1969).

Hutchinson, Kansas - 1924. Several feet of subsidence involving city buildings including the court house and jail took place in 1924 (Young, 1926). H. C. Bunte, City Engineer, reports (personal communication) that no further settlement has been observed and that a shopping center is under construction over the center of the original settlement area.

Grand Saline, Texas - 1955. Subsidence in a brine field; area backfilled, terrain put back to use.

Choctaw Salt Dome, Louisiana. A sinkhole resulting from salt production occurred in 1934(?), caused a minor disruption to operations. The area remains in production today.

Borger, Texas. A sinkhole developed over the cavity of brine wells serving a salt cavity storage terminal.

Tully, New York. Several sinkholes dating back to the 1930's resulting from salt well operation have formed in this brine field. No attempt is made to back-fill. The subsidences are accepted as routine.

Saltville, Virginia. The valley floor of Holston River has several acres of subsidence reported to have sagged as much as 20 feet. A state highway has been relocated to higher ground. This is one of the older artificial brine operations in the United States.

Windsor, Ontario - 1954. Perhaps the best-documented example of sinkhole formation related to salt production, prior to the present instance, occurred at the brine field of Canadian Industries Limited in 1954. Records are available as to salt

production, well operation, elevation observations, and eye-witness accounts. The depression has been back-filled, a railroad siding traversing the area rebuilt, and operations resumed. Figures 15 and 16 are photographs taken from the same position in 1954 and 1971. The 1954 photo shows the Windsor sinkhole shortly after its occurrence. The 1971 photo shows the site after restoration to use by back-filling the hole and construction of railroad tracks. A main generating station of the Canadian Hydropower System is located nearby and was undisturbed by this event.

The Solution Mining Research Institute has undertaken an investigation of this event to attempt to determine the mechanism which operates in the formation of a sinkhole related to salt production. The study will include a review of available data, with further drilling if required to provide additional information.

Summary. It is generally recognized that salt extraction by the classical method of well operation results in subsidence of the surface either as downwarp, or in some instances as a sinkhole. Only a few of the better-known examples are listed here. These are cited to illustrate that subsidences are widespread, but upon termination of the activity are relatively easily accommodated disruptions to the environment. It is important to note that surface effects are confined to the area overlying the salt cavities - neighboring areas are not involved.

Collapsed Underground Mines

Mining, near the surface and mostly of coal, has been followed by the partial or complete abandonment of overlying communities, especially in eastern Pennsylvania and western Wyoming, due to the slumping of the surface into the underlying workings. Hopefully, the greater depth of current mines, and the public insistence that adequate pillars of coal or ore be left intact or that openings be back-filled, will prevent such occurrences in the future. Note, however, that only the surface overlying the mined area was involved in slumping and collapse; neighboring areas remain intact.

Pumping of Oil and Water and Even Sand in Oil Country

The flowing and pumping of enormous quantities of oil, and accompanying water, from beneath the surface rarely results in noticeable disturbance of the surface. The reason is that most oil accumulations are underlain by water under head; this water moves in immediately to replace the withdrawn fluids. However, there are exceptions, and two examples follow. The reader should keep in mind that these are examples of subsidence caused by removal of fluids from porous sediments which then allows the sediments to compact, resulting in settlement. They are cited here for completeness of treatment of the causes of settlements. In the Grosse Ile case, no porous sediments are involved; the salt is overlain by hard rocks, and surface effects are confined to the brine field itself.

Goose Creek oil field - Harris County, Texas. This field on the Gulf Coast about 25 miles southeast of Houston began producing in 1916, with some wells yielding
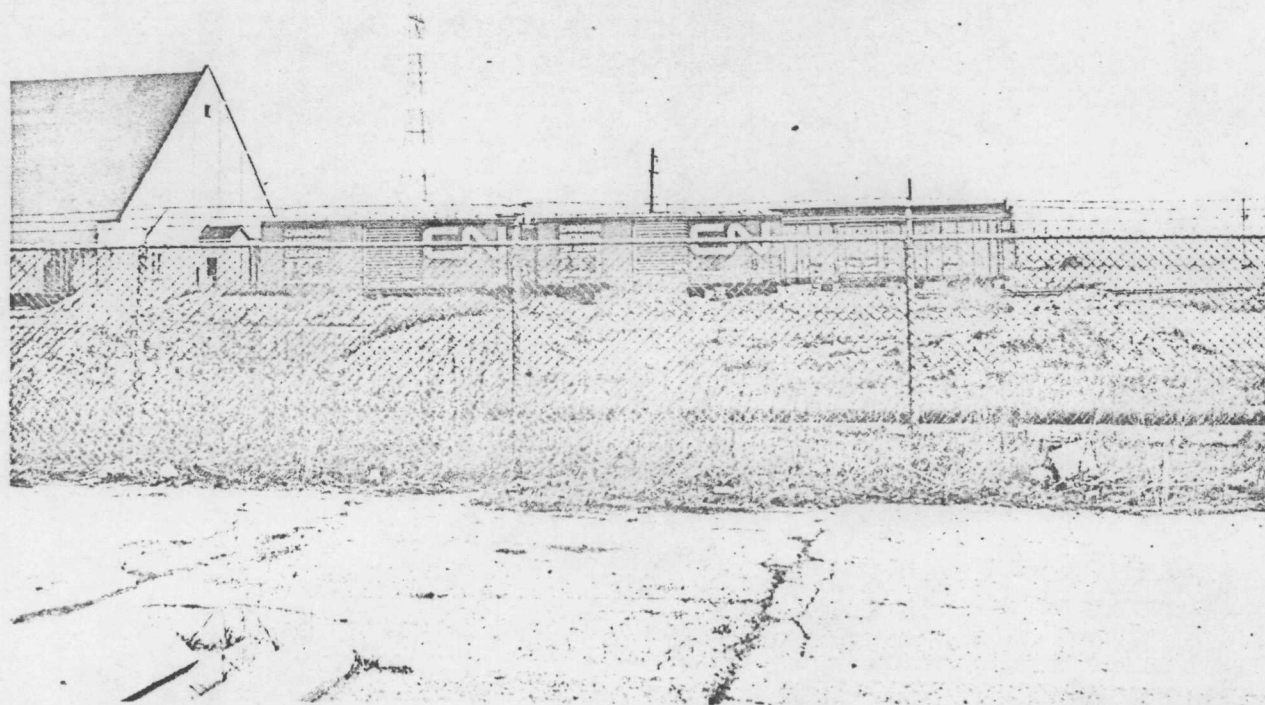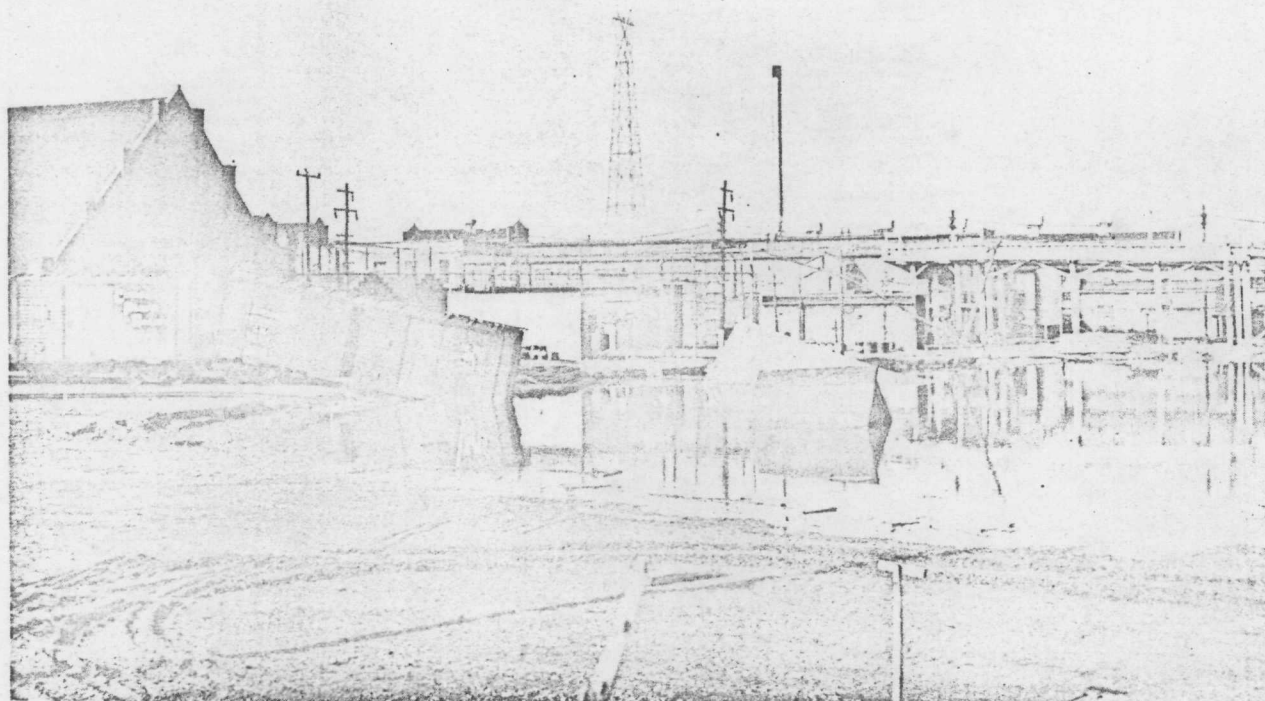
Figures 15 & 16

Views of sinkhole at Windsor, Ontario, 1954. Above: Scene at the time of the subsidence.
Below: Scene today after restoration by backfilling.

as much as 35,000 barrels per day. During this flush production a marked subsidence of the surface overlying the center of the field took place. Land that had original elevations of 1/2 to 2 feet above high tide subsided enough to inundate the area beneath 2 to 3 feet of water. This sagging of the surface is thought to be due to the pumping of sand and water (which causes compaction of the shales) along with oil from the reservoir about 1600 feet below (Pratt and Johnson, 1926; Snider, 1927).

Wilmington-Long Beach area, California. The area where subsidence accompanied oil removal lies almost at sea level. Surface subsidence to a maximum depth of 29 feet necessitated construction of a dike to keep the Pacific Ocean from inundating this highly industrialized section of Long Beach. The settling is ascribed to the removal of fluids from porous sediments without adequate subsurface replacement. Further settlement was retarded by pumping sea water into the reservoir at a rate of over one million barrels (42 million gallons) a day. As a bonus this restoration of reservoir pressure also increased daily production of oil by 50,000 barrels (Smith and Schambeck, 1966, p. 313).

Water Removal Only

The draining of a marshy area will result in compaction and subsidence. The surface of the English fenlands has been lowered 13 feet since 1848 due to drainage projects.

In at least one instance the mere pumping of water from dolomitic bedrock underlying weathered residium up to 1000 feet in thickness resulted in catastrophic sinkhole development in an urban area (Jennings, 1966; Foose, 1967; Quinlan, 1972). The ill-fated project was for the purpose of dewatering gold mines in the Far West Rand district near Johannesburg, South Africa. Quoting Quinlan: "As of June 1968 more than 200 sinkholes, some as large as 375 feet wide and 150 feet deep or 20 feet wide and 300 feet deep, had formed. Thirty-four lives have been lost. Approximately 35 million dollars has been spent on rebuilding, application of safety measures, research, and compensation for damage and loss of water supplies".

Acts of God

Sinkholes and other depressions numbered in the millions are not the result of man's activities, but are produced by normal geological processes. Although these processes have been going on throughout geologic time, most of the sinkholes we see today are relatively new because other geological activities tend to either erode away or cover up these and other topographic features. The sinkhole cycle is a simple one: (1) dissolution of caverns underground by circulating ground waters; (2) collapse of the cavern roof to the surface; and (3) removal of the hole in the ground by either the wearing away of the surface down to and below the original cavern floor, or (more rarely) the filling of the sink by inwashed sediment.

Obviously the original solution cavern cannot develop unless relatively soluble rocks are present. These rocks are limestone (including dolomite), salt, and gypsum. By far the most soluble rock in this list is salt, with gypsum second and carbonate rocks (limestone and dolomite) third. Although in comparison with salt, carbonate rocks do not appear to be soluble, ground waters with abundant carbon dioxide in solution can and do dissolve enormous caverns (Mammoth Cave, Carlsbad Caverns, and many others) in these rocks. Furthermore, limestone is a very abundant rock at and near the surface in many parts of the world, so limestone sinkholes are plentiful, whereas salt and gypsum sinkholes are much fewer. Other, but less common, depressions resulting from dissolution are swamps, valleys, and even major lakes.

Examples of sinkholes and other results of the leaching of soluble rocks follow.

Natural sinkholes. In many limestone areas the surface is so pockmarked with sinks that neither a straight road nor agricultural pursuits are possible. Where the rainfall is such that the water table is shallow each sinkhole contains a lake. The physiographic term to describe such topography is "karst", named after a sink pitted limestone plateau in western Slovenia, Yugoslavia, north of Trieste on the Adriatic. In west central Jamaica a bizarrely scenic karst area is called the "Cockpits".

Many limestone floored parts of the eastern United States, especially Kentucky (Quinlan, 1970) and Florida are karstic. Actually any area with limestone at or near the surface is subject to sinkholing. Sinkholes occur in Alpena County, in the north-eastern part of Michigan's Southern Peninsula, where limestones crop out. One of these is normally occupied by a lake, which has the unfortunate habit of completely flushing through a sub-sink channel every few years.

The common evaporites, salt and gypsum, are also subject to dissolution by natural underground waters. A most striking pair of sinkhole lakes due to evaporite leaching and collapse is shown in the accompanying photograph (Figure 17). These are the Mirror Lakes in the Bottomless Lakes State Park along the Pecos River near Roswell in southeastern New Mexico. In size, shape, and juxtaposition, but not in topography and geologic structure, they look like the Central Gallery sinkhole lakes on northern Grosse Ile. Furthermore, there is a remarkable similarity in origin. Quinlan (1967) ascribes the original dissolution to upward leakage of artesian water in the Roswell artesian basin that passes through gypsum (and salt locally) on its way to the surface. The Grosse Ile twin lakes are due to a man-made artesian movement that dissolved salt while travelling between the input and the brine production wells.

Solution collapse structures of natural origin in the Province of Saskatchewan have been described (DeMille, Shouldice, and Nelson, 1964). The soluble rocks are evaporites in the Prairie Formation of Devonian age.

Sinkholing has been witnessed in at least two localities in Kansas. An acre of land in Pawnee County (west central Kansas) sank in 1898, taking with it a railroad station as well as some track. Pawnee County lies west of the subcrop of the westward dipping Permian salt measures that are exploited by mines and brine wells in central Kansas. The other occurrence, in Hamilton County in far western Kansas, was seen by
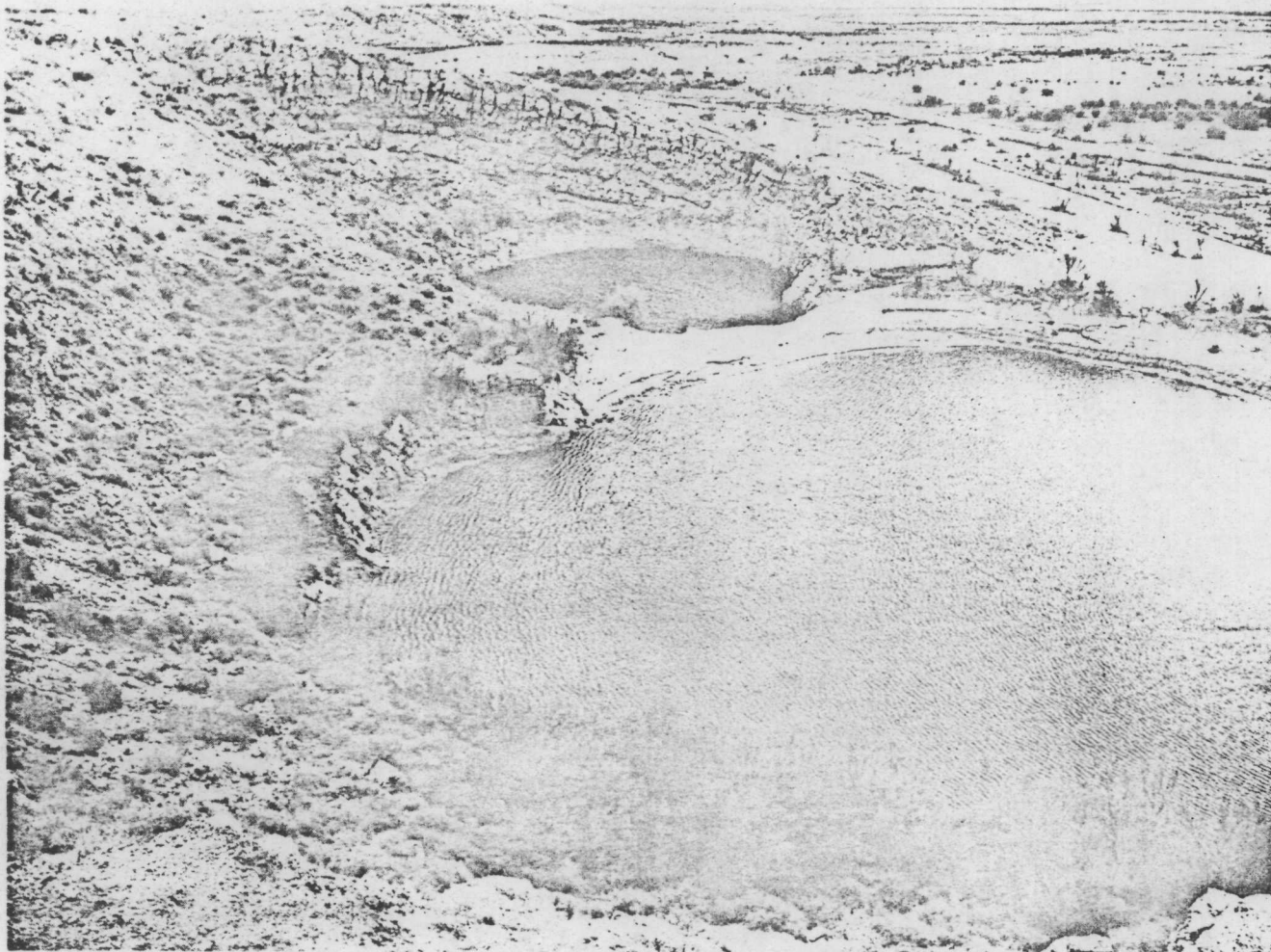
Fig. 17 Roswell, New Mexico.
Natural Sinkholes Resulting From Action of Groundwater on Soluble Rock.

Photo Courtesy James F. Quinlan

one of us (Landes) a few weeks after sudden subsidence took place. This circular sinkhole broke through to the surface on 18 December, 1929, and in time sloughing of the walls extended the rim outward until a public road and right of way has been engulfed. Also in Hamilton County is an older sink used by livestock as a watering hole (Bass, 1931, p. 205, Figure 2). The soluble rock involved in these sinkholes is ascribed by Bass (op. cit., p. 204) to Cretaceous limestone and by Landes (1931) to deeper evaporites, perhaps Triassic gypsum.

Swamps. Swamps and shallow depressions overlie the solution-eroded outcrop of the Permian salt measures in central Kansas. Landes, while with the State Geological Survey of Kansas, visited the locale of a sudden sagging of the surface in McPherson County that took with it a small bridge across an already depressed swampy area. Similar collapsing where shallow salt or gypsum is being actively dissolved by percolating water has been noted elsewhere (Landes, 1963).

Valleys. In submountcinous regions containing steeply dipping thick limestone ledges erosion by solution of these limestones results in "chemical valleys". In these elongate depressions stream erosion has played a secondary role in sculpturing the topography. The Great Valley of Virginia, lying between the Blue Ridge on the east and the Allegheny Mountains is a well known example. This depression continues north-northeastward from Virginia across the panhandles of West Virginia and Maryland and into southern Pennsylvania where it turns east-northeastward and crosses Lebanon County. Limestone quarries, mines, and sinkholes occur along this trench over a distance of more than 400 miles. The Natural Bridge, which is utilized by a major highway, near Lexington in the Shenandoah Valley of Virginia, is all that is left of the roof above a cavern dissolved from limestone. The cave was elongate, and through it flowed an underground river. The collapse of most of the roof exposed the stream, which runs under the bridge.

The physiography of Centre County, Pennsylvania, is likewise dominated by chemical valleys. In some of these the uneven valley floors are so pocked with sinks that the rivers mostly run underground. The management of a new limestone mine on the south side of Nittany Valley in Centre County thought that it had the waste water disposal problem solved when they discharged mine water into a sinkhole where it gurgled out of sight, until the state fish hatchery across the valley some miles away reported that all of a sudden all their fish were floating upside down!

Major lakes. The Mackinac Straits, which separates the northern and southern peninsulas of Michigan and connects Lakes Michigan and Huron, is generally conceded to be a collapse feature resulting from large scale salt removal (Landes, 1959). Furthermore, these connecting Great Lakes themselves in part occupy the outcrop belt of major salt measures in this area.

-44-

Environmental Effects

Introduction. Michigan Act. No. 315 of the Public Acts of 1969 explicitly states that "a person shall not cause surface or underground waste (of natural resources) in the drilling, development, production, operation, or plugging of wells subject to this act".

This section of our report is an appraisal of the effect of the Point Hennepin sinkholes on the environment.

Underground waste. The hydrogeology of Grosse Ile is discussed earlier in this report under Ground Water. The underground water is divided into free and confined water. Free water occurs in the surface soil zone outside of the area covered by tailings; it is not under head and drains into the river on both sides of Grosse Ile. The soil is very thin due to the fact that it is largely derived from glacial clay containing scattered boulders. The water in it is quantitatively insignificant, and its quality is poor due to the presence of products of decay from the organic material in the original surface swamp.

The uppermost confined ("artesian") water occurs immediately beneath the glacial drift that seals it in. It is stored in the upper part of the bedrock, partly in a soil zone at the top, but especially in intersecting joint cracks cutting the solid rock. This water is potable, providing that one likes its characteristic sulfurous odor and taste. In high concentration the hydrogen sulfide gas is lethal; its escape into excavations has resulted in many deaths in southeastern Michigan. This relatively shallow confined bedrock aquifer is connected with the Detroit River through the intersection of joint cracks in the rock-walled main channel. Therefore its head is controlled by the level of the river.

Deeper in the bedrock section are layered aquifers which when penetrated by a borehole produce artesian flows with heads up to 20 feet above river level. An important artesian water source on southern Grosse Ile is the Sylvania Sandstone; the water from this basal unit of the Detroit River Group is also sulfurous. The Swan well (described in the section on Ground Water, above) has been discharging sulfur water into a short tributary of the Detroit River for nearly 70 years.

The local collapse of the surface on northern Grosse Ile in early 1971 was accompanied by both an inflow of river water and an upward flow of sulfurous water

from Detroit River Formation strata. This water partially filled the newly formed craters; it has been sealed in laterally by the impermeability of the tailings overburden. It slowly declines toward river level by outflow through the soil zone on top of the bedrock, and through fissures in the bedrock. However, the occasional breaking away of large segments of crater wall that fall and slide into the pool temporarily raises the water level and the slow subsidence of the water level resumes. During the time the crater water level is above river level there no doubt is some subsurface outflow of crater water into the river. However, the quantity of sulfur water thus discharged into the river is not significant. Without doubt the contamination of the Detroit River by sulfurous bedrock waters through both natural outflow from outcrops and the continuous discharge of the Swan well makes this insignificant by comparison. This contamination is not long lasting, for much of the hydrogen sulfide in solution escapes into the air.

The natural waters occurring below the Sylvania Sandstone are too mineralized to be potable, as is the Sylvania water a few miles down dip from the outcrop. However, even though saline, these waters are too lean in sodium chloride and other dissolved salts to be of any economic value. It is therefore concluded that there has been no economic loss or damage to this resource.

Some concern has been expressed that the collapsing of cavern roofs, with chimney-like connections with the surface, would permit the mixing of the saturated cavern brines with higher waters. In our opinion this is unlikely, for even if the collapse material filling the chimneys is permeable, the saturated brine would have difficulty penetrating potable water because of the 20 per cent greater density (1.2) of the brine. By our conception of sinkhole formation wherein roof rock falls to the cavity floor and the cavity thus grows upward by stoping to form a chimney, no decrease in volume occurs. Roof rock drops to the floor, changing place, but cavity volume does not diminish. No brine was extruded to fill the craters. The minor chloride content in crater water samples can be attributed to inflow from 14 inch brine mains that were ruptured at the time of the initial craterings and to residual liquors leached from waste bed material collapsed into the crater.

The following chemical analysis of a water sample collected from the southern sinkhole on 4 June, 1971, 36 days after collapse, more closely matches the composition of the tailings pile including the contained transporting liquor than it does brine cavern water.

	Mg/L
Total Solids	97,320
Total Solids Vol.	1,280
Suspended Solids	8

	Mg/L			Mg/L
Total P	0.35	CHCl$_3$ Ext.		1.6
Na+	35,800	Mn		0.17
Ca++	2,160	Fe		0.2
Mg++	12	SO$_4$		2030
Cl-	57,500	pH		11.6
Hg	0.0073			
S--	7	Sp. Gr. 25/25		1.0675
C.O.D.	571			

Possible other "subsurface resources" overlying the salt beds are clay, dolomite, and glass sand. These are of no value on Hennepin Point because of the unlikelihood of profitable removal. This is discussed under "Possible Economic Products" in the section on "Geology".

Surface waste. The State guidelines refer to waste of surface waters, soils, animal, fish, and aquatic life, and property damage. All of these potential wastes can be disposed of quickly except the last, property damage.

The subsurface movement of sulfurous ground water into the Detroit River was mentioned in the preceding section on "Underground Waste". Upon joining the river it becomes surface water, regardless of whether the original source was a flowing well or laterally seeping ground water. At the time of the collapsing of the surface, and the partial filling of the craters by water from beneath, there was no visible outflow of water into the river channels on either side of Point Hennepin, and therefore no overland pollution of surface waters.

The cratering of the surface on northern Grosse Ile destroyed no soil, for there was none there to destroy. The 30 feet of chemical plant waste that covers the original swampy surface has not been exposed to weathering the many decades necessary to transform this recalcitrant material into soil.

There has been no evidence of any damage whatsoever to either the flora and fauna, which are sparse in the area covered with chemical plant waste, or to aquatic life in the Detroit River.

The local collapse of the surface on northern Grosse Ile has resulted in very local displacement of surface property. Whereas before the land was relatively flat along the top of the waste pile, there are now one small single crater above the North Gallery and one larger crater with satellite above the Central Gallery. These can be seen in the air photographs (Figures 9 and 10). The walls of the craters are steep, due to the cohesiveness of the fine waste particles. This produced a safety hazard, necessitating the temporary employment of guards. The northern crater has been partially filled and the walls sloped. Plans have not yet crystallized for the treatment to be given the Central Gallery crater.

The high level of public concern over the Grosse Ile sinkholes was due to the fear that the entire area was undermined and residences nearby would be engulfed. It has been shown here that the sinkholes are centered on, and confined to, the two main brine well galleries. Further confirmation has been from precise level surveys of reference bench marks on northern Grosse Ile that show early indications of arrest (Figure 18) duplicating the record for the North Works 20 years earlier (Figure 8).

There is another aspect to surface subsidence that is more psychological, or emotional, than the situation may actually warrant. The sudden dropping of the surface, caused by the collapse of the roof of an underground cavern, may cause near-panic in surrounding areas not undermined by brine galleries and where, therefore, surface collapse is impossible. This reaction is unfortunate, but it is also understandable.

Profitable use of brine caverns. Important uses for which brine cavities can be utilized include storage of natural gas, liquefied petroleum gases (LPG), gasoline, fuel oil, and crude oil. Such openings can be used also for disposal of liquid pollutants, radioactive wastes, other noxious wastes, and solid waste (in slurry form). Not the least of these wastes to be disposed are from the salt plant that created the cavities in the first place. A perhaps important use now under study is for storage of compressed air during off peak demand for electrical energy; the compressed air is utilized for the generation of electricity during high demand periods. Deep solution caverns in the Gulf Coast salt domes, where the temperatures reach 500°F and above, may be tapped some day as a source of geothermal energy (Jacoby, 1971).

As of now the major use of brine caverns has been for the storage of liquefied petroleum gases (propane, butane, etc.). This has become a major industry near large cities. As an example, currently an oil company is in the process of dissolving 7 large caverns, with capacities of nearly 200,000 barrels (8,400,000 gallons) each, in the salt in southeastern Michigan. The total cost for these storage cavities, plus a deep well for the disposal of excess brine, is estimated to be about one million dollars. Gas companies are also searching for salt cavities for off-season storage of natural gas. One cavern in a brine field near Port Huron is so used today.

In other words, by ceasing production in salt galleries ahead of collapse, the operators could perhaps more than compensate for the greater cost per ton of the salt produced, due to higher unit cost charged to cavern development, by the sale or lease of cavern space. Jacoby (1971) states, "It is probable that in the future the cavity created by solution mining will be more valuable than the salt".
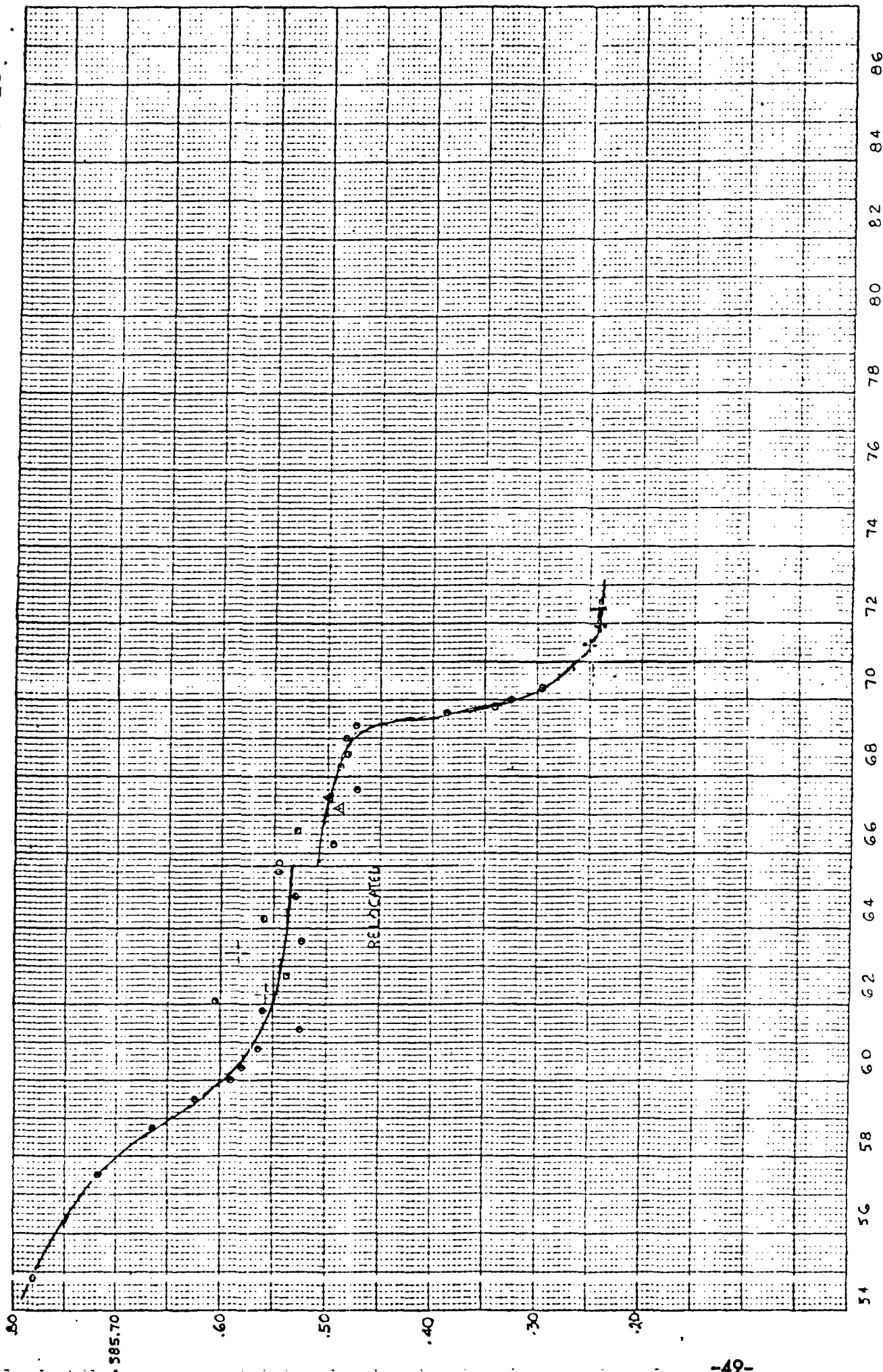
TIME VS. SETTLEMENT PLOT OF A GROSSE ILE NORTH GALLERY REFERENCE POINT SHOWING CHANGE IN SLOPE AFTER TERMINATION OF PRODUCTION

Wyandotte

GROSSE ILE WELL No. 20.

By: Kenneth K. Landes, Thomas B. Piper

Sponsored by: Solution Mining Research Institute and BASF Wyandotte Corporation

April 1972

-49-

The Grosse Ile sinkholes, covering areas of 7 acres (above the North Gallery) and 15 acres (Central Gallery) are within the limits of their dissolved caverns, and for within the 250 acre extent ot the brine field. It is apparent, one year later, that surface equilibrium has been re-established here, as it has been at Windsor and in other areas where earlier collapsing has taken place.

It is our opinion that these sinkholes have produced no significant damage to the resources or the environment. Conversely, the Point Hannepin brine field has made an important contribution to the society by supplying millions of tons of salt for the benefit of the public.

BIBLIOGRAPHY

Bass, N. W., 1931, Recent subsidence in Hamilton County, Kansas: Bull. Amer. Assoc. Petrol. Geol., V. 15, no. 2 (Feb.), p. 201-205.

Cook, Charles W., 1914, The brine and salt deposits of Michigan: Mich. Geol. and Biological Survey, Pub. 15.

DeMille, G.; Shouldice, J. R.; Nelson, H. W., 1964, Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Geol. Soc. America Bull., V. 75, no. 4, p. 307-316.

Fuller, Myron L., 1905, Contributions to the hydrology of the United States: U. S. Geol. Survey, Water Supply and Irrigation Paper No. 145, p. 142-143.

Gail, Charles P., 1954, The application of the freezing method to shaft sinking: Canadian Mining and Metallurgical Bulletin, Sept., p. 586-589.

Garvey, P. L., Oil and gas in Essex County, Ontario: Dept. of Geol., Univ. of Mich., unpublished Masters thesis. Feb. 5.

Hewitt, D. F., 1962, Salt in Ontario: Ontario Dept. of Mines, Industrial Mineral Report No. 6.

Jacoby, Charles H., 1971a, Cavity utilization: Am. Inst. Mining Eng., Ann. Mtg., 2 March, preprint.

Jacoby, Charles H., 1971b, Evaluation of salt deposits: manuscript submitted to the Amer. Inst. Mining Eng. for publication, 13 May.

Jacoby, Charles H., 1971c, Disposal of salt plant wastes in abandoned brine cavities: Am. Inst. Mining Eng., Environmental Quality Conference, 7 to 9 June, preprint.

Jaron, Michael G., 1970, Investigation of solution collapse breccia in mature salt cavities: The Northern Ohio Geol. Soc. (Cleveland), Third Symposium on Salt, V1, p. 422-428.

Jennings, J. E., 1966, Building on dolomites in the Transvaal: The Civil Engineer in South Africa (Transactions of the South African Institution of Civil Engineers), V. 8, No. 2 (January), p. 41-62.

Knutilla, R. L., 1971, Water resources of the River Rouge basin, southeastern Michigan: U. S. Army Corps of Engineers, Hydrogeologic Investigations Atlas HA - 356, Sheets 1 and 2.

Landes, Kenneth K., 1931, Recent subsidence, Hamilton County, Kansas: Bull. Amer. Assoc. Petrol. Geol., V. 15, no. 6, (June), p. 708.

Landes, Kenneth K., 1945a, Mackinac breccia, in Geology of the Mackinac Straits region by K. K. Landes, G. M. Ehlers, and G. M. Stanley: Michigan Geological Survey, Pub. 44, Chapter 3, p. 123-154.

Landes, Kenneth K., 1945b, The Salina and Bass Island rocks in the Michigan Basin: U. S. Geol. Survey, Oil and Gas Invest. Prelim. Map no. 40.

Landes, Kenneth K., 1951, Detroit River Group in the Michigan Basin: U. S. Geol. Survey Circular 133, September.

Landes, Kenneth K., 1963, Effects of solution of bedrock salt in the earth's crust: Symposium on Salt, Northern Ohio Geological Society (Cleveland), p. 64-73.

Male, K. O., 1969, Salt: a policy for the control of salt extraction in Cheshire (draft document). Cheshire County Council, Chester, England.

Piper, Thomas B., 1954, Report on the formation of a sinkhole related to brine production, Sandwich, Ontario, Feb. 19, 1954: Wyandotte Chemicals Corp., Internal Report.

Quinlan, James F., 1967, Sinkholes formed by upward leakage of artesian water through gypsum: Christmas card, privately published, 4 p.

Quinlan, James F., 1970, Central Kentucky Karst: Reunion Internationale Karstologie en Langueduc-Provence, 1968, Actes: MEDITERRANNEE, Etudes et Travaux; No. 7, p. 235-253.

Quinlan, James F., 1971, Collapse sinkholes and subsidence depressions caused by ground water pumpage in ar urban area in the Transvaal Karst, South Africa: origin and detection of incipient development: Caves and Karst, V. 13, No. 5 (September/October), p. 44.

Sherzer, W. H., 1913, Geological report on Wayne County: Mich. Geol. and Biological Survey, Pub. 12.

Young, C. M., 1926, Subsidence around a salt well: Trans. Am. Soc. Min. and Met. Engineers, V. 74, p. 810-817.